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National Oceanic and Atmospheric Administration
Environmental Research Laboratories
Seattle WA 98115

United States
Environmental Protection
Agency

Office of Environmental Engineering
and Technology
Washington DC 20460

EPA-600/7-79-252
December 1979

Research and Development

Dynamics of Port Angeles Harbor and Approaches Washington

Interagency Energy/Environment R&D Program Report

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DYNAMICS OF PORT ANGELES HARBOR

AND APPROACHES, WASHINGTON

by

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Prepared for the MESA (Marine Ecosystems Analysis) Puget Sound Project, Seattle, Washington in partial fulfillment of

EPA Interagency Agreement No. D6-E693-EN
Program Element No. EHE625-A

This study was conducted
as part of the Federal
Interagency Energy/Environment
Research and Development Program

Prepared for

OFFICE OF ENVIRONMENTAL ENGINEERING AND TECHNOLOGY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

September 1979

Completion Report Submitted to
PUGET SOUND ENERGY-RELATED RESEARCH PROJECT
MARINE ECOSYSTEMS ANALYSIS PROGRAM
ENVIRONMENTAL RESEARCH LABORATORIES

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This work is the result of research sponsored by the Environmental Protection Agency and administered by the Environmental Research Laboratories of the National Oceanic and Atmospheric Administration.

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LIST OF ABBREVIATIONS

ABBREVIATIONS	
CGAS	-- Coast Guard Air Station
CTP	-- conductivity-temperature-pressure
CZ	-- Crown Zellerbach, Inc.
EHI	-- Evans-Hamilton, Inc.
EPA	-- Environmental Protection Agency
FI	-- Fiberboard, Inc.
ITT	-- ITT Rayonier, Inc.
mgd	-- million gallons per day
NOAA	-- National Oceanic and Atmospheric Administration
PBI	-- Pearl-Benson Index
PDT	-- Pacific Daylight Time
ppm	-- parts per million
Sigma-t	-- (density in gm cm^{-3} -1.0) x 1000.
SWL	-- sulfite waste liquor

ABSTRACT

Historical oceanographic data in Port Angeles Harbor, located behind a spit on the northern coast of Washington, have been analyzed with emphasis on the physical processes that transport and disperse spilled oil. The data base spans 1932-1979 and includes observations of tides, currents, winds, runoff, water properties, oil spills, suspended sediment, and pulp mill effluent. Because of the fragmentary distribution of the data base a hydraulic tidal model was used to provide additional continuity in space and time of tidal flows within the Harbor and several miles of the shore.

The plan view of mean circulation near the surface in the approaches consists of westward flow at mid-channel and an eastward countercurrent within several miles of the U.S. shore. Experiments in the hydraulic tidal model and a 19-day current record suggest a tidally induced weak mean circulation (order of 1 cm s^{-1}) eastward in the Harbor near the surface. The variance of currents observed in the Harbor was about twentyfold greater than expected from the rise and fall of local Harbor tides. The anomalous variance is attributed principally to two local features: forcing by exterior flows that are fiftyfold more energetic; and westerly winds that prevail most of the year. Their combined effects yielded a residence time of several days to a week for near-surface water in the Harbor.

Patterns of suspended sediment, pulp mill effluent, and drift sheet and drift card movement showed a tendency for net eastward flow along the shore, and dispersion by tidal eddies offshore and onshore. Drift cards released in Port Angeles Harbor reached a wide area including Sequim and Discovery Bays, Admiralty Inlet, Whidbey Basin, the Strait of Georgia, Fidalgo, Vancouver, and the San Juan islands. Observations of an oil spill showed that some oil can be mixed downward and carried into Puget Sound by the net inland estuarine flow at depth.

1. INTRODUCTION

1.1 GENERAL STATEMENT

Port Angeles Harbor (hereafter the Harbor) is a small embayment inside a spit located on the northern coast of Washington toward the head of the Strait of Juan de Fuca (Fig. 1.1). The Harbor has long been a shipping port because of its depth, weak tidal currents, and protection from the waves afforded by the spit, Ediz Hook. A considerable number of logs are shipped from the Harbor to the Orient. In addition there are numerous recreational vessels often within the Harbor and its approaches.

Recently it was proposed that tankers dock in the Harbor and discharge petroleum through submarine pipelines to storage facilities that may be located onshore at Green Point (Fig. 1.2; Bureau of Land Management, 1979). The prospect of increased shipments of petroleum through the Strait of Juan de Fuca has resulted in an investigation of the fate of petroleum that may be accidentally discharged into the subject waters (see Baker et al., 1978).

Major industrial facilities in the area include two pulp mills that discharge through offshore diffusers. Effluent from Crown Zellerbach, Inc. is discharged through an outfall in the Strait of Juan de Fuca at the longitude of the Harbor's head; and effluent from ITT Rayonier, Inc. is discharged at a location eastward of the Harbor's mouth and close to the route of the proposed submarine petroleum pipelines.

The subject waters are noted for a great diversity of marine life. Examples of commercial sealife include the Coho, Chinook, Chum, and Pink salmon that spawn in the local rivers and creeks, halibut (Egan, 1978), clams (Goodwin and Shaul, 1978), and Dungeness crabs. At Dungeness Spit there is a national wildlife refuge.

1.2 OBJECTIVES

The interaction of petroleum and other material inputs with the biological and chemical processes is undoubtedly complex. Here we report a synthesis of physical aspects of circulation that bear on the dispersion of material inputs concentrated primarily near the water surface in the Harbor and its approaches.

The behavior of petroleum on the water surface is variable in time and space. Physically, after spillage, oil spreads, drifts, and disperses as patches and filaments at the water surface, and also may be mixed to depth.

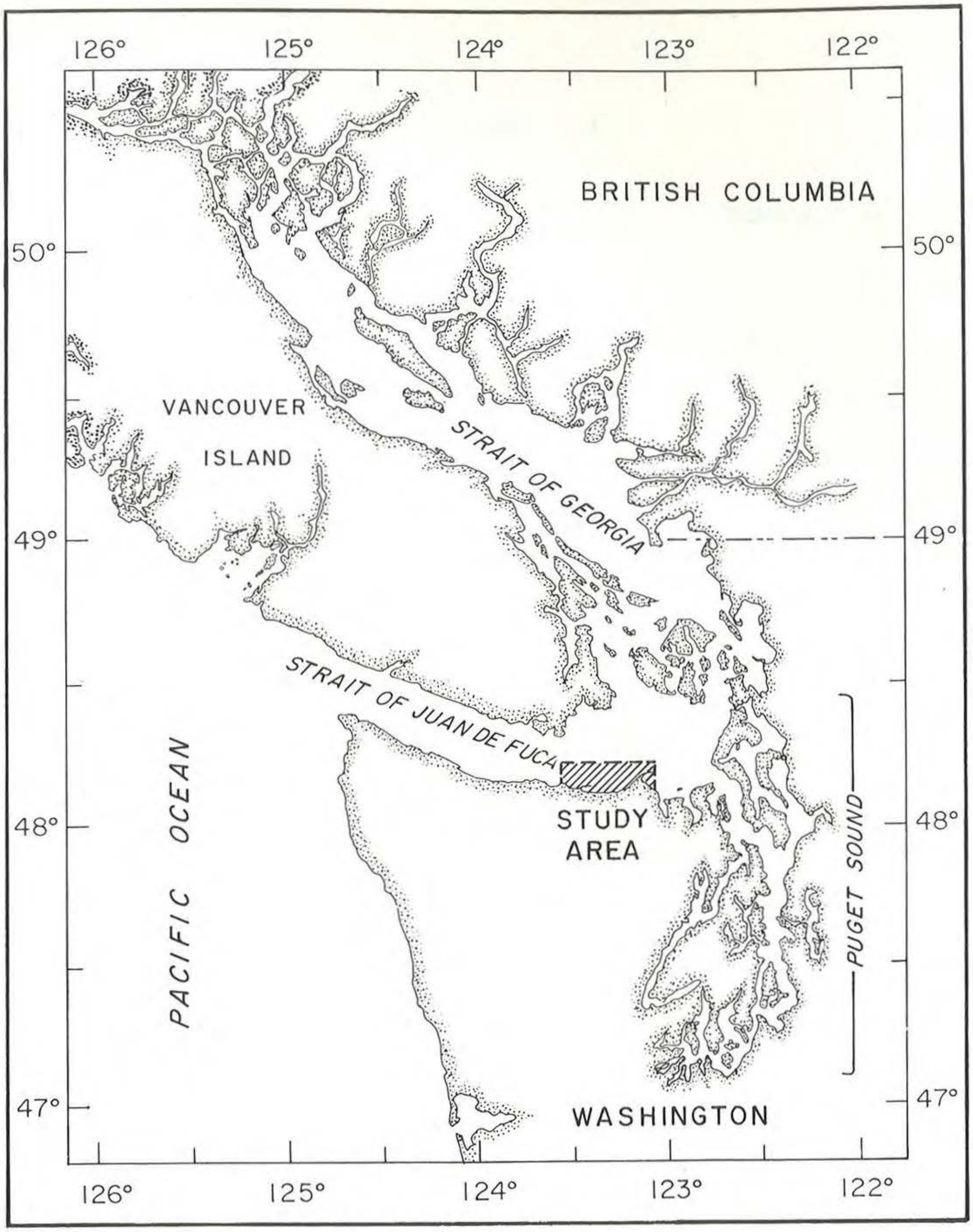

Figure 1.1. Study area (hatched) and approaches.

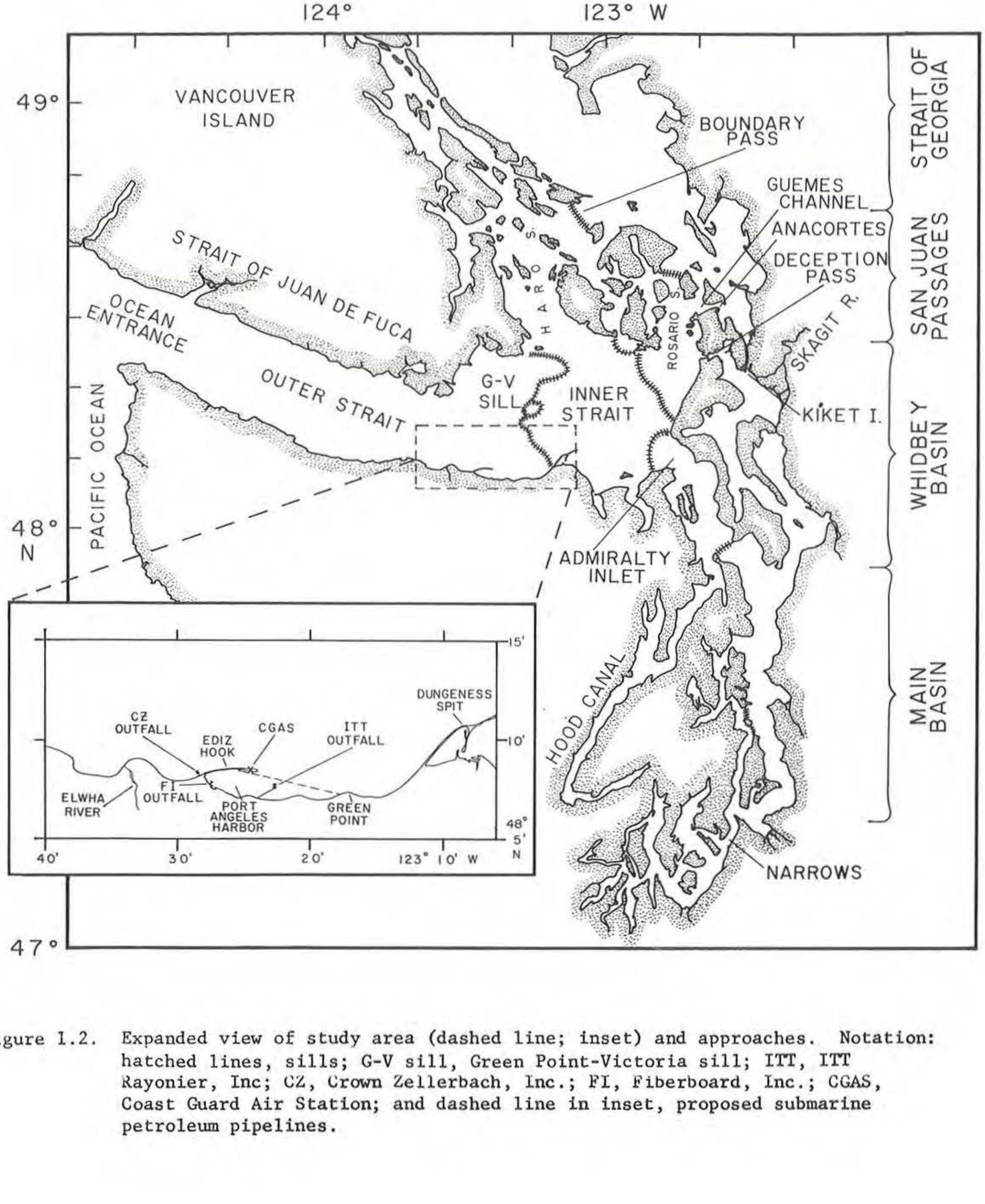

Figure 1.2. Expanded view of study area (dashed line; inset) and approaches. Notation: hatched lines, sills; G-V sill, Green Point-Victoria sill; ITT, ITT Rayonier, Inc; CZ, Crown Zellerbach, Inc.; FI, Fiberboard, Inc.; CGAS, Coast Guard Air Station; and dashed line in inset, proposed submarine petroleum pipelines.

Many aspects of the behavior of spills have been summarized by Stolzenbach, et al. (1977). The present study addresses the portion of dispersion where the petroleum may be treated as a passive contaminant that drifts primarily at the water surface.

The major objective of this report is to obtain patterns of circulation near the water surface using existing data of water properties and currents supplemented with observations of water movement in a hydraulic tidal model. Although there have been a significant number of individual field investigations, for the most part these have been conducted over short spatial and temporal intervals. There has been neither an extensive, long-term program designed to obtain circulation patterns, nor a synthesis of the oceanographic data collected during previous studies.

For clarity the results of this research have been presented in six chapters. In remaining sections of this chapter the pertinent aspects of the geography of the study area are described; in Chapter 2 the sources of field data and the hydraulic tidal model are described; in Chapter 3 the mean and fluctuating flows are characterized; in Chapter 4 the characteristic time scales of water movement in the Harbor are analyzed; in Chapter 5 the dispersion of material inputs is discussed; and in Chapter 6 the major conclusions are summarized.

1.3 GEOGRAPHY

The study area encompasses a variety of prominent geographical features. The inner Strait of Juan de Fuca has bathymetry that is highly irregular consisting of a complex of channels and banks (Fig. 1.3). Shallowest depths may be traced from the U.S. shore between Green Point and Dungeness Spit to the Canadian shore on Vancouver Island (Fig. 1.2). This sill has an average depth of approximately 60 m and greatest depth of 115 m which is offset from mid-channel toward the U.S. For clarity this sill will be referred to as the Green Point-Victoria sill.

At the western edge of the study area there is a major lateral constriction of the Strait of Juan de Fuca. It is bounded by submarine projections of Vancouver Island on the north and of the Elwha River delta on the south (Fig. 1.3). At this cross section the mid-channel depth is approximately 210 m.

The characteristic dimensions of the Harbor have been summarized in Table 1.1 based on recent bathymetric charts. At the Harbor's mouth there is a sill-like feature (approximately 44 m depth); westward the Harbor depths increase to approximately 59 m (Fig. 1.3). The entrapment interval between sill and basin depths is approximately 15 m. The surface area of the Harbor is approximately 9 km^2, of about 0.6% of the surface area of the inner Strait of Juan de Fuca.

Some of man's activities in the area have drastically reduced the amount of sediment transported alongshore that is necessary to maintain the configuration of Ediz Hook (see Pacific Northwest Sea, 1974). Prior to 1930 there

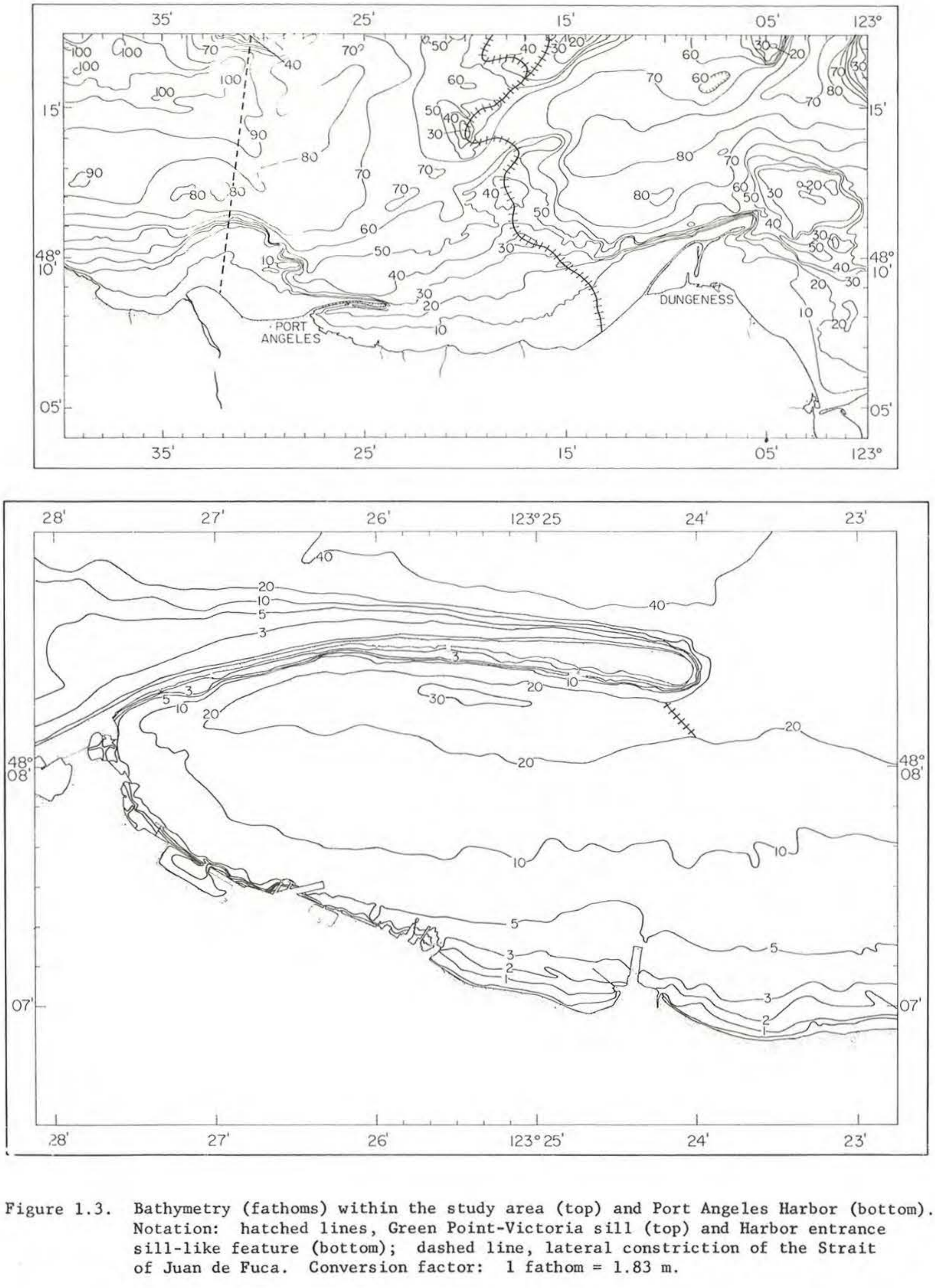

Figure 1.3. Bathymetry (fathoms) within the study area (top) and Port Angeles Harbor (bottom). Notation: hatched lines, Green Point-Victoria sill (top) and Harbor entrance sill-like feature (bottom); dashed line, lateral constriction of the Strait of Juan de Fuca. Conversion factor: 1 fathom = 1.83 m.

were two major sources of sediment; the Elwha River and the cliffs between the Elwha River and Ediz Hook. In 1910-1911 and 1925-1928 dams were constructed on the Elwha River and in 1930 a water supply line and rock covering were constructed along the base of the cliffs. It has been estimated that the dams and pipeline protective rocks together resulted in about a 75% decrease in the sediment that nourishes Ediz Hook. Since these projects were completed Ediz Hook has significantly eroded and a number of attempts have been made to stabilize its present shape. In the event that the shape is significantly changed some of the results of this report may no longer be applicable.

TABLE 1.1. CHARACTERISTIC DIMENSIONS AND RATIOS OF PORT ANGELES HARBOR[a].

Dimensions	$\times 10^6$	units
1. Volume below mean lower low water	209.	m^3
2. Volume between mean lower low and mean higher high waters	20.7	m^3
3. Harbor area at mean lower low water	9.31	m^2
4. Cross sectional area of Harbor entrance	0.0519	m^2
5. Harbor length, entrance to head	0.00444	m
Ratios	$\times 10^0$	units
6. Bulk residence period = Volume (1)/ Tidal prism (2)	10.1	
7. Characteristic tidal speed = tidal prism (2)/cross sectional area (4)/ quarter tidal day	0.0177	$m\ s^{-1}$

a West of 123° 24'W longitude.

2. METHODS

Data presented in this report have been collected from a variety of sources and consist of observations made in the field (2.1) and in a hydraulic tidal model (2.2).

2.1 FIELD DATA

Data were obtained from municipal, state, federal, and private institutions for the period 1932-1979. Materials reviewed contained data on the tides, currents, winds, runoff, and water properties of the Harbor and vicinity. In addition suspended sediment, pulp and paper mill effluent, and two oil spills were used as tracers of material input movement. Sources of the field data are listed below.

2.1.1 Tides

The National Ocean Survey Tide Tables list predictions of tides for the eastern end of Ediz Hook. The mean range (1.3 m) is defined as the difference in height between mean high water and mean low water. The spring range is the average semidiurnal range occurring semimonthly as the result of the moon being full. The diurnal range (2.2 m) is the difference in height between mean higher high water and mean lower low water.

2.1.2 Currents

Currents have been measured using current meters and a variety of drifting objects. Summaries of current meter measurements spanning less than several days are listed in Appendix A.1. These measurements were generally taken at approximately hourly intervals using over-the-side current meters lowered to depth for periods of ten to twenty minutes. Current meter records spanning longer periods (5-41 days) were obtained from the National Oceanographic Data Center, National Ocean Survey, and the EPA. Most of these measurements were taken using Aanderaa current meters. The times, depths, and locations of these measurements are listed in Appendix A.2.

Data were obtained of the movements of three types of drifting objects: small plastic cards, thin flexible plastic sheets, and drogues tethered at selected depths (Appendix A.3). Recoveries onshore of several thousand drift cards released in the Harbor and its approaches have been tabulated by Ebbesmeyer et al. (1978) and Pashinski and Charnell (1979). The trajectories of several hundred drift sheets were obtained by Ebbesmeyer et al. (1978) and Cox et al. (1978) in the study area during daylight using a small aircraft. Drogue movements during several hour periods have been reported by Charnell (1958), Tollefson et al. (1971), the EPA (1974), and Ebbesmeyer et al. (1978).

2.1.3 Winds

The patterns of prevailing winds over the Strait of Juan de Fuca have been summarized by Harris and Rattray (1954) and Cannon (1978). For comparison with water behavior in the Harbor mean hourly wind speed and direction (1947-1952) were obtained at the U.S. Coast Guard station located near the eastern end of Ediz Hook (see Fig. 1.2).

2.1.4 Runoff

Monthly average river discharge data were obtained for the Elwha River (1961-1970), Dungeness River (1961-1970), Morse Creek (1966-1970), and Siebert Creek (1961-1970) from the U.S. Geological Survey (1971 and 1974). The runoff data for the Strait of Georgia (1950) were that of Waldichuk (1957) and the data for Puget Sound were determined from monthly average discharge data (1951-1970) using Lincoln's (1977) technique.

2.1.5 Water Properties

Prior to the introduction of modern electronic field equipment, water properties were taken throughout Puget Sound and the Strait of Juan de Fuca by the University of Washington and Canadian institutions at rather widely spaced stations disregarding tides. These stations have been tabulated through 1966 by Collias (1970): temperature, salinity, and dissolved oxygen commonly have been sampled at mid-channel monthly during selected years since 1932.

Recently many coordinated measurements of water properties and currents have been made in the Strait of Juan de Fuca primarily by the National Oceanic and Atmospheric Administration (NOAA) and the Environmental Protection Agency (EPA). Currents have been recorded several times per hour for periods lasting months and conductivity-temperature-pressure (CTP) systems have been used to provide closely spaced data on vertical profiles. These observations have been partially summarized by Cannon (1978).

In the Harbor and close approaches a number of surveys have been done since 1950, most lasting only a short period of time (see Appendix A.4). However, during 1963-1964, monthly samples were taken at several locations inside the Harbor and at a reference station located approximately 2 km north of the tip of Ediz Hook (Callaway et al., 1965). These data have been described by Bartsch et al. (1967) and were used herein to determine seasonal cycles in the Harbor and in adjacent waters.

2.1.6 Suspended Sediments

At times there are significant amounts of sediment contained in the local runoff. Sediment input to the marine waters from the Elwha River and cliff erosion west of Ediz Hook have been estimated by the U.S. Army Corps of Engineers (1971).

2.1.7 Pulp and Paper Mill Effluent

Monthly average effluent discharges were obtained for three mills: ITT Rayonier, Inc. (ITT), Crown Zellerbach, Inc. (CZ), and Fiberboard, Inc. (FI; see Fig. 1.2 for locations). At present only two mills remain in operation, the FI mill discontinued operations in 1970. Discharge data prior to 1966 have been presented by the Washington State Pollution Control Commission (1967). Discharge data from 1966-1974 were obtained from the Washington State Department of Ecology (formerly the Washington State Pollution Control Commission). Discharge data after 1974 were obtained from the EPA.

2.1.8 Aerial Photographs

Aerial photographs of the study area were obtained from several sources as listed in Appendix A.5 and examined for patterns of suspended sediment and pulp and paper mill effluent.

2.1.9 Oil Spills

In 1971 approximately 880 m^3 (230,000 gallons) of Number 2 diesel oil was spilled at the Texaco refinery near Anacortes, Washington (see Vagners and Mar, 1972). Some oil was subsequently detected in water drawn from depth inland of Deception Pass in Puget Sound by personnel from the University of Washington. Description of oil movement was obtained from Professor Clifford A. Barnes.

On 13 May 1979 at 1020 (Pacific Daylight Time, PDT) approximately 2.3 m^3 (600 gallons) of Number 4 fuel oil was spilled from the commercial vessel ATLANTIC HORIZON at the mouth of the Harbor. Data on the spill's dispersion were collected in the form of photographs on 14 May between 1400-1500 by personnel from NOAA and Evans-Hamilton, Inc. (EHI). The photographs were taken from a small aircraft at approximately 300 m altitude.

2.2 HYDRAULIC TIDAL MODEL

The field data taken at various tidal phases do not provide the continuity in time and space needed for an adequate representation of tidal currents and associated patterns of contaminant dispersion. In order to provide a framework for synthesis of the field data a hydraulic tidal model was constructed of the Harbor and its approaches. Because the tidal flow is affected by physical characteristics over a large area, the western portion of the Strait of Juan de Fuca and landward was modeled (Fig. 2.1). The small size of the model makes possible synoptic observations over a large area, and the compressed time scale enables observations over many days to be taken in an hour.

2.2.1 Model Scales

The model was constructed using length and time scales listed in Table 2.1. The scales were determined from physical reasoning similar to that used in the construction of a comparable size model, the hydraulic tidal model of

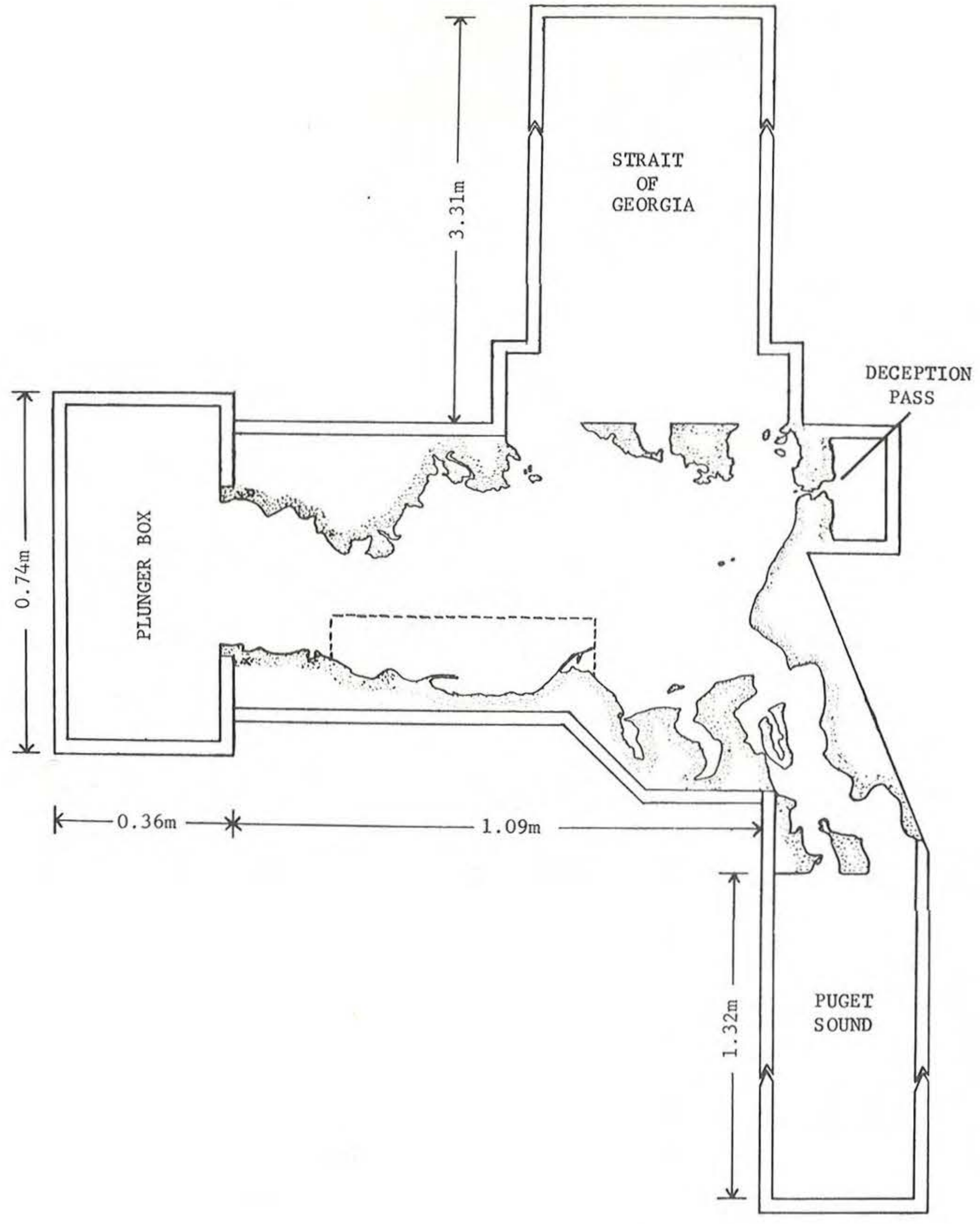

Figure 2.1. Schematic of the hydraulic tidal model. Notation: dashed line, study area.

Puget Sound located at the University of Washington, Seattle, Washington (see Barnes et al., 1957). The Puget Sound Model has been in operation since the early 1950's and has compared favorably with observed field conditions (Rattray and Lincoln, 1955).

TABLE 2.1. MODEL SCALES FOR THE HYDRAULIC TIDAL MODEL OF THE STRAIT OF JUAN DE FUCA.

Scale Parameter	Ratio	Prototype Value		Model Scale Value
Horizontal distance	1:80,000	1 kilometer	=	1.25 cm
Vertical (depth)	1:1,440	1 meter	=	0.069 cm
Time	1:2,108	24 hours	=	41.04 secs
Speed (horizontal)	1:38.0	$1\ m\ s^{-1}$	=	2.63 cm/s

The horizontal scale was limited by construction costs and available space. The vertical scale (depth) has been exaggerated by a factor of approximately 56 in order that turbulent flow occurs at most tidal phases in the study area, and also that the effects of surface tension are reduced. The time scale was determined by equating tidal wave speed in the prototype with that in the model.

The bathymetry was accurately sculpted from depths shown on National Ocean Survey Chart numbers 18421, 18441, and 18465. The construction consisted of a matrix of vertical rods cut proportionate to each chart depth. Concrete was poured between the rods and up to their ends so as to form a smooth bottom.

The tides were generated by a plunger in a container located at the seaward end of the model. The vertical displacement of the plunger was controlled by a mechanical system of gears. It reproduced two tidal frequencies dominant at the plunger location. The frequencies were adjusted slightly in order to obtain a tide curve which repeats daily. The tidal volumes of the Strait of Georgia and Puget Sound were simulated by rectangular boxes having proportionate length, width, and average depth. In Puget Sound the tidal volume divides near the Skagit River where water to the south ebbs toward Admiralty Inlet and water to the north ebbs toward Deception Pass. Separate boxes were used to simulate these two tidal volumes.

Wind effects were not modeled.

The effects of earth rotation are significant in the Strait of Juan de Fuca (see Herlinveaux and Tully, 1961) but were not included because of practical considerations. Despite this limitation there are certain features of tidal flow generated by shoreline irregularities that can be modeled in the study area. Some of these features are evident in photographs of the model that may be compared with field data.

2.2.2 Model Photographs

For comparison with field measurements of currents, water movement in the tidal model was determined using the following photographic technique: 1) the water was dyed with black (India) ink and the surface was sprinkled with bronze dust; 2) the shutter interval of a camera mounted overhead was set at one second (approximately 35 minutes in the prototype) with the result that movements of the dust particles on the water surface appeared as streaks in the photographs; and 3) streak photographs were taken at short intervals through a tidal day. Similar techniques have been used by Collias *et al*. (1973) and McGary and Lincoln (1977) to obtain patterns of tidal currents in the hydraulic tidal model of Puget Sound. Tidal current patterns were interpreted from the photographs and were rendered by an artist for clarity to show flow direction but not speed.

Streak photographs were obtained with the tide generating machine set to approximate spring tides. Appendix B.1 shows the times through the tidal day corresponding to each current pattern. The tidal current patterns are shown in Appendix C.1-C.32.

Because of the slower tidal current speeds in the Harbor additional photographs were made of the Harbor using a shutter interval of two seconds. Examples of streak photographs of the Harbor are shown without interpretation in Fig. 2.2.

2.2.3 Model Verification

The streak photographs were compared primarily with patterns of drogue and drift sheet movement in the Harbor and its close approaches. The comparisons were distributed through a tidal day (Appendix B.1) and are shown for convenience with corresponding model current patterns in Appendix D.1-D.13. Most of the current patterns reported by various investigators were found in the model patterns at respective tidal phases.

The comparisons are considered reasonable despite the following limitations: 1) field data were obtained on a variety of tidal phases differing from the spring tides used in the tidal model experiment; 2) observations of the drifting objects occurred at longer intervals than the 35 minute interval corresponding to streaks in the photographs (i.e., some details of drifter movements were obscured because of comparatively long sampling intervals); and 3) wind conditions for the field observations are unknown except for those of Ebbesmeyer *et al*. (1978) where data used in the comparison with the model were selected from periods when winds were less than 5 knots.

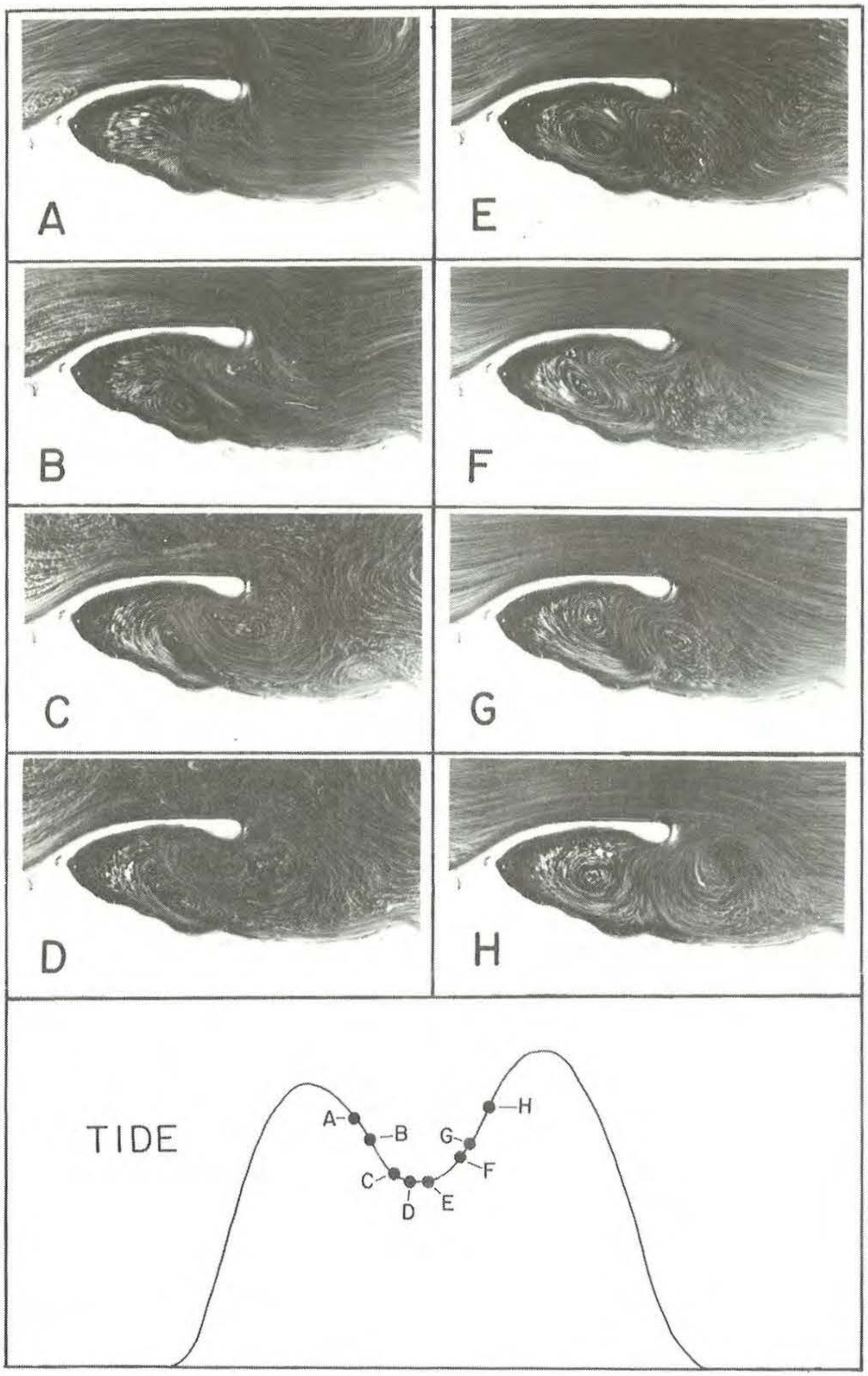

Figure 2.2. Selected streak photographs of Port Angeles Harbor in the hydraulic tidal model. Camera shutter interval was set at two seconds. Notation: A-H, tidal phases shown at bottom.

3. FLOW CHARACTERISTICS

The currents that affect contaminant dispersion may be divided into mean and fluctuating components. Each component has contributions from several mechanisms including those associated with tides, winds, runoff, and intrusion of oceanic source water. Although the data base is insufficient to identify the relative contributions of the various mechanisms it is useful to quantify their overall effects as summed in the two components. The mean is characterized by its speed and direction, and the fluctuations are characterized by variance about the mean which is proportional to kinetic energy.

3.1 MEAN CURRENTS

The vertical section at mid-channel of mean flow from the Strait of Juan de Fuca into the Strait of Georgia has been diagrammed by Waldichuk (1957) following Redfield (1950), and into Puget Sound by Barnes and Ebbesmeyer (1978; Fig. 3.1). In the northern portion of the study area near mid-channel this pattern consists of flow toward the west at depths shallower than approximately 50 m, and eastward flow at greater depth.

Currents have been measured using recording current meters for periods from 5-41 days at 13 sites within the study area. Though the records were obtained at various times using different equipment, for perspective the results have been combined in plan views of current means and variances near the surface (approximately 5 m depth; Figs. 3.2 and 3.3). The time series of individual records are shown in Figure 3.4. Cannon (1978) has estimated the reliability of selected mean currents near the surface. His computations suggest that the mean currents were relatively steady during the observational periods for sites 1, 2, 3, 5, and 12. Computations were not given for other sites and depths.

Although the records are not synoptic, they do indicate the following patterns. Near the shore between Ediz Hook and Dungeness Spit the mean flow is eastward apparently from surface to bottom. The speed of the near-shore current apparently increases toward the east, the flow off Dungeness Spit being comparable to that at mid-channel. Within the Harbor one current meter was moored at mid-depth for nineteen days (Site 1). There is a weak mean current eastward at a speed of 0.013 m s^{-1}.

3.2 KINETIC ENERGY

The measured variance in the current meter records provides an

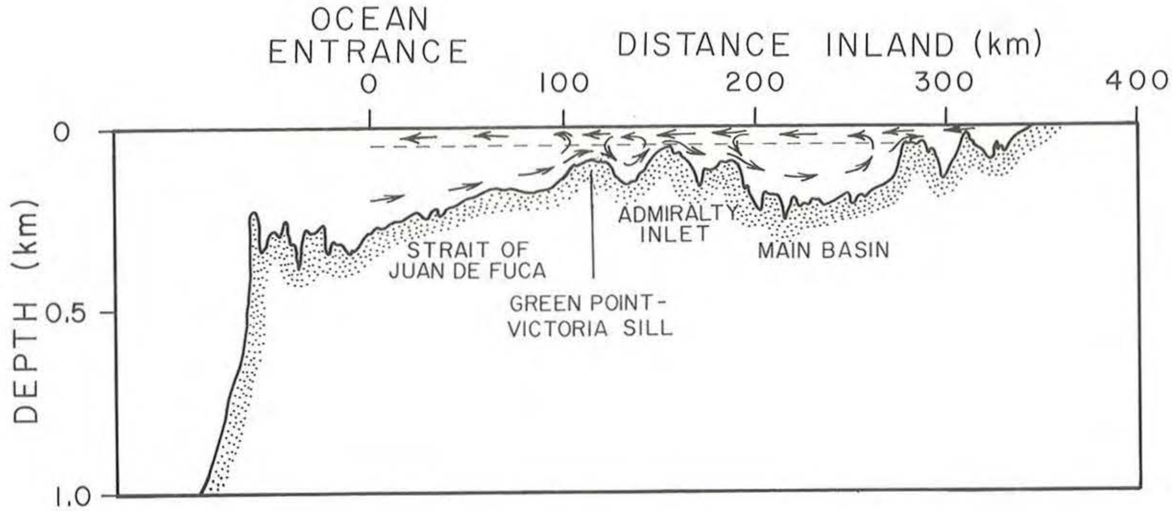

Figure 3.1. Profile view of net circulation at mid-channel in summer between the Pacific Ocean and the head of Puget Sound (adapted from Ebbesmeyer and Barnes, 1979). Notation: dashed line, depth of no-net-motion (approximately 50 m).

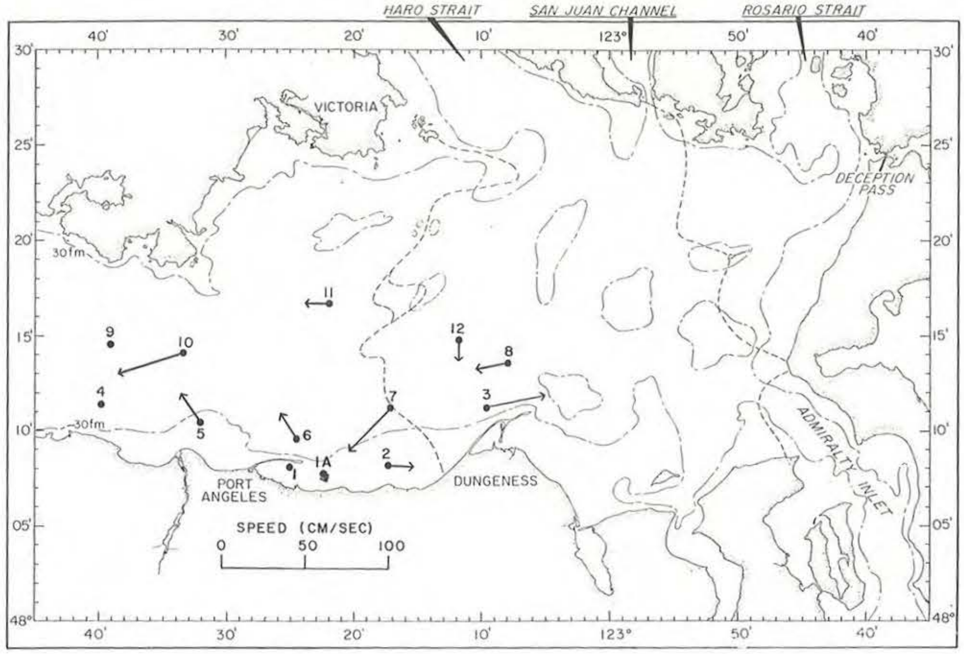

Figure 3.2. Plan view of mean currents near the surface (approximately 5 m depth) from longer period current meter records. Dots without arrows lack current meters at 5 m depth. Site numbers correspond to data shown in Appendix A.2. Notation: dashed lines, selected sills.

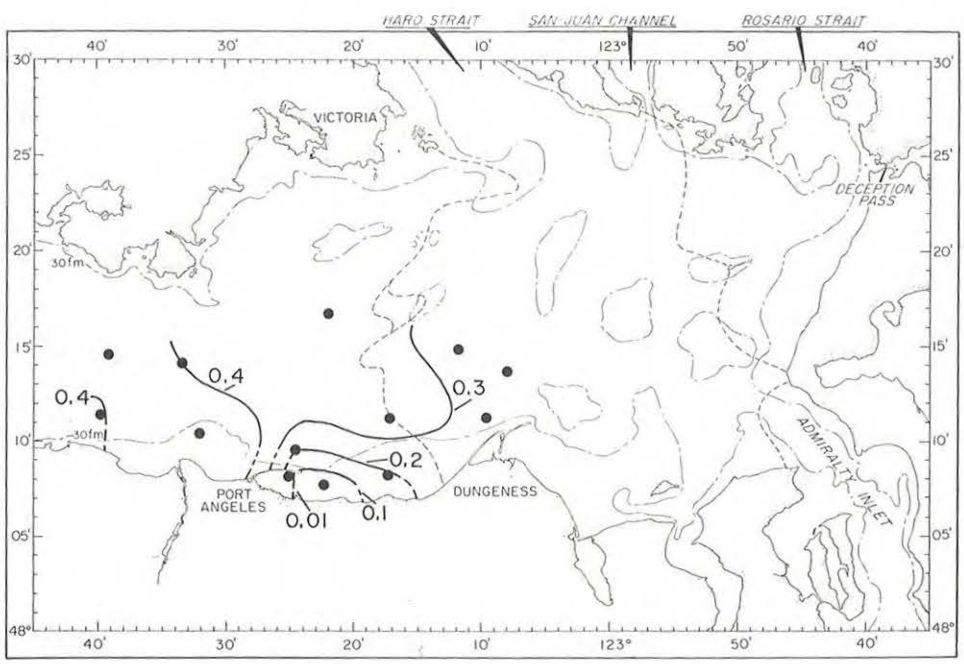

Figure 3.3. Plan view of variance near the surface (approximately 5 m depth) of longer period current meter records. Note change in contour interval between 0.1 and 0.01 m^2 s^{-2}. Notation: dashed lines, selected sills.

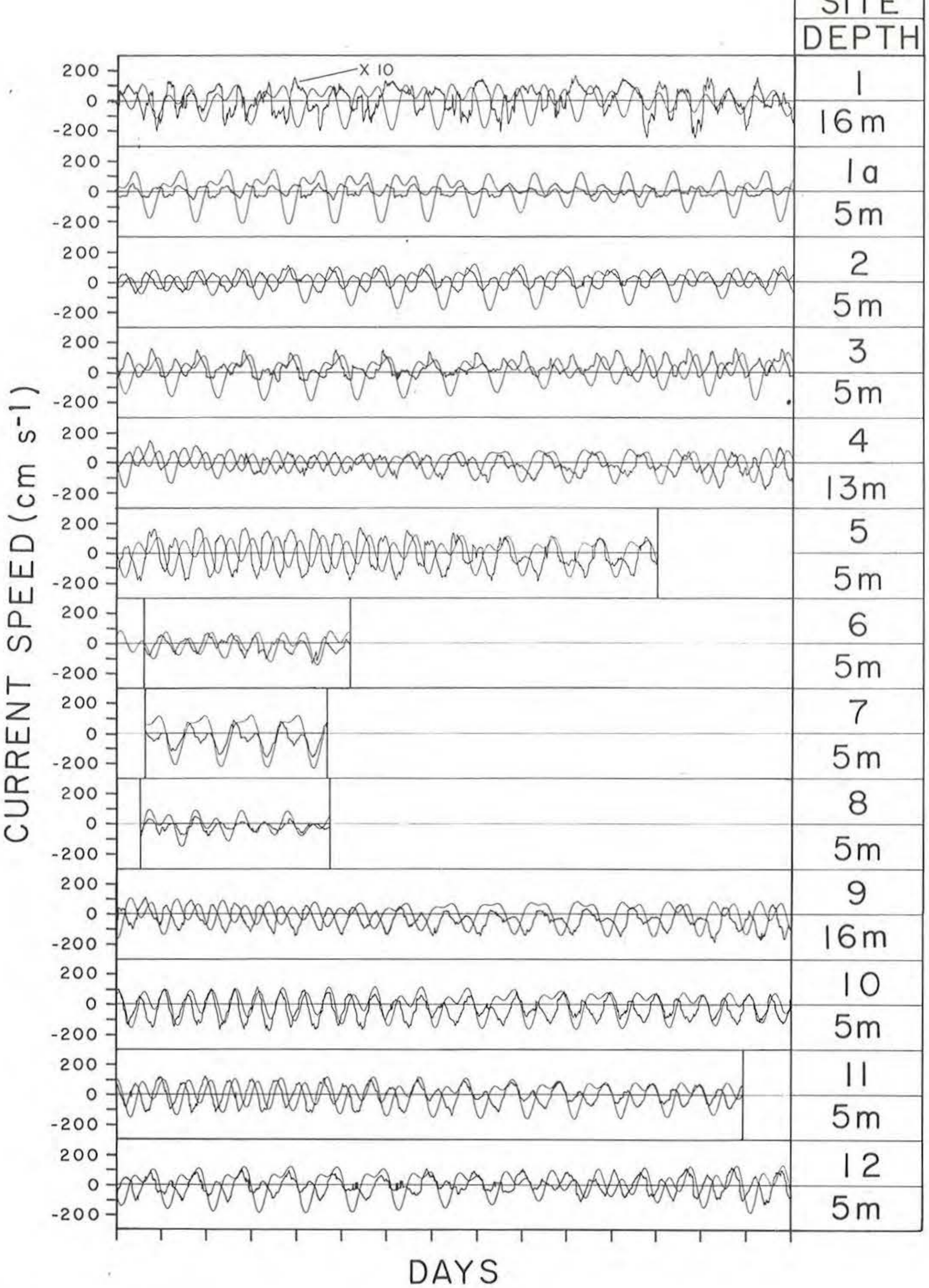

Figure 3.4. Time series of longer period current meter records. Sites of current meter moorings are shown in Figure 3.2 and listed in Appendix A.2. Smooth lines represent predicted tides at Port Angeles and other lines are observed current speeds where positive and negative are reckoned toward the east (001-180° True) and west (181-360° True), respectively.

indication of the kinetic energy (KE) that might be available for the mixing of contaminants. The KE associated with tides has been computed by Ebbesmeyer and Barnes (1979) from the ocean entrance through Puget Sound's Main Basin (Fig. 3.5). The KE represents the average at a cross section (A) during a quarter tidal day (Δt), and was computed as $KE = (TA^{-1}\Delta t^{-1})^2$, where T is the change in volume associated with the diurnal tidal range landward of the cross channel section.

The impact of tidal mixing may be illustrated by a comparison of the annual average longitudinal distributions of the freshwater fraction and oxygen saturation near the bottom with KE computed from tides. The KE in the inner Strait of Juan de Fuca apparently is severalfold higher than in the outer Strait. The oceanic source water that traverses the outer Strait near the bottom shows comparatively small changes in freshwater and oxygen, whereas there are sharp increases in the more energetic inner Strait.

The plan view of measured variance within the study area is shown in Fig. 3.3. The pattern consists of lowest values in the Harbor and much higher values in the surrounding waters. In the Harbor at Site 1 (16 m depth) currents typically reach speeds of 0.1 m s^{-1} and have a variance of 0.0071 m^2 s^{-2}. This value is approximately equal to the variance (0.0066 m^2 s^{-2}) estimated from drogue movements observed in the Harbor by Ebbesmeyer et al. (1978). Although the variance in the Harbor appears small it is actually twentyfold larger than the KE of 0.00031 m^2 s^{-2} computed for tides alone.

The anomalous energetics of the Harbor may be shown in a comparison of computed tidal KE and measured variance for selected cross sections of Puget Sound and the Strait of Juan de Fuca (Fig. 3.6). For present purposes the variances are those from currents measured in The Narrows and Admiralty Inlet by Cannon et al. (1979), Puget Sound's Main Basin by Cannon and Laird (1972), and the study area as listed in Appendix A.2. The computed tidal KE corresponding to the locations of the current measurements are from Ebbesmeyer and Barnes (1979) as shown in Figure 3.5. There is an approximate correlation except for the Harbor: its variance is twentyfold higher than expected from the computed KE indicating that other mechanisms are contributing to circulation in the Harbor. Two major contributors to this energy surplus appear to be tidal eddies and local winds.

3.3 TIDAL EDDIES

Patterns of surface tidal currents as determined from the hydraulic tidal model are shown in Appendix C.1-C.32. There are eddy-like patterns evident at all tidal stages. In this study patterns of movement that appear closed have been termed tidal eddies. The eddies are transient features; during their existence there may not be sufficient time for a hypothetical water particle to traverse their circumference.

Despite the complexity that is often apparent in the tidal current patterns, there are several general types of eddy behavior. During the early flood or ebb phases tidal eddies develop to the lee of most shoreline

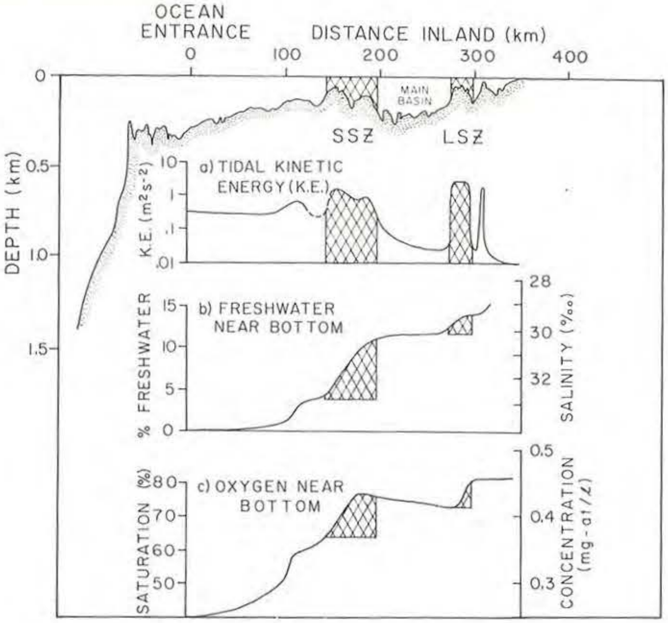

Figure 3.5. Profile distributions at mid-channel (Pacific Ocean to head of Puget Sound) of: a) tidal kinetic energy; b) near bottom freshwater percentage and salinity; and c) near bottom oxygen saturation and concentration (from Ebbesmeyer and Barnes, 1979). Data from Barnes and Collias (1956a, b) November 1953-December 1954 in b) and c). Notation: SSZ, seaward sill zone; LSZ, landward sill zone for Puget Sound Main Basin.

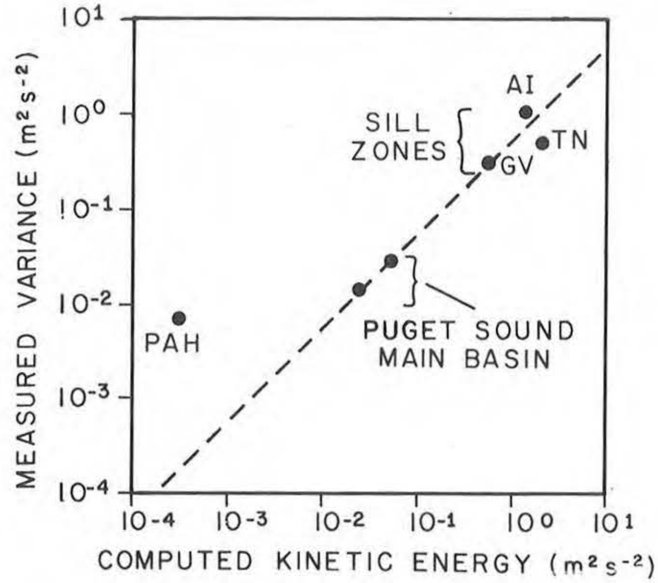

Figure 3.6. Kinetic energy computed from tides versus variance from current meter measurements. Notations: PAH, Port Angeles Harbor mouth; AI, Admiralty Inlet; GV, Green Point-Victoria sill; TN, The Narrows. Variance data: PAH, Appendix A.2; Puget Sound, Cannon and Laird (1972); TN, Cannon et al. (1979); GV, Appendix A.2; AI, R. Muench, personal communication.

irregularities. The eddies grow in size from the beginning of both floods and ebbs. In order to demonstrate this growth the mean diameters of eddies which develop east and west of the Elwha River delta and east of Ediz Hook were scaled from the streak photographs (Fig. 3.7). The diameter growth with time at the three sites is approximately linear at a rate on the order of 0.6-0.7 km $hour^{-1}$. During major ebbs and floods the diameters of eddies increase as much as tenfold. Since the area contained within an eddy increases approximately as the diameter squared, some eddy areas increase a hundredfold.

Near the end of a tidal phase at high and low waters some of the eddies apparently are displaced from their growth sites and decrease somewhat in diameter. As they migrate away from shore they contribute to the irregular flow patterns that are evident near high and low tides. Thus it is near so-called slack tides that greatest dispersion rates of surface contaminants are likely to occur.

Tidal eddies are often apparent within the Harbor (Appendix C.1-C.32). These eddies do not circulate as rapidly as those exterior to the Harbor noted above, and their size is constrained by the Harbor's dimensions. As a result the flow in the Harbor tends to be more complex than that in its approaches.

The model studies suggest that eddy flows in the Harbor are driven by the more energetic exterior tidal flows. The exterior forcing is most likely a major contributor to the energetic behavior of the Harbor noted earlier. The computations of tidal KE assume that the tidal flow is uniformly distributed over the cross section at the Harbor's mouth. However results from the hydraulic tidal model suggest that the actual pattern is significantly non-uniform. Thus greater volumes of water can be exchanged on a given flood or ebb than with uniform flow.

3.4 WIND EFFECT

Figure 3.8 shows the seasonal progression of prevailing winds. The study area is unique in that throughout the year the winds are typically from the west. A six-year record of hourly winds taken at the eastern end of Ediz Hook showed that the mean hourly speed was directed from the west except in January when the direction was south-south-east. Highest mean speeds occurred in July and lowest values occurred in February and October.

Although the distribution of wind stress with depth in the study area has not been determined it is well known that wind effects are often most pronounced near the water surface. Sulfite waste liquor (SWL) is concentrated near the surface and may be used as a tracer of the gross effect of wind. Figure 3.9 shows both the concentration and cumulative amount of SWL in the Harbor versus depth as averaged during summer (June-September) and fall-spring (October-April). Fifty percent of the SWL was shallower than 3 m and ninety percent was contained in the upper 15 m. In the Harbor wind effects are evident in a comparison of the seasonal cycles of total SWL (i.e., integrated over the Harbor's volume) with the seasonal cycle of mean

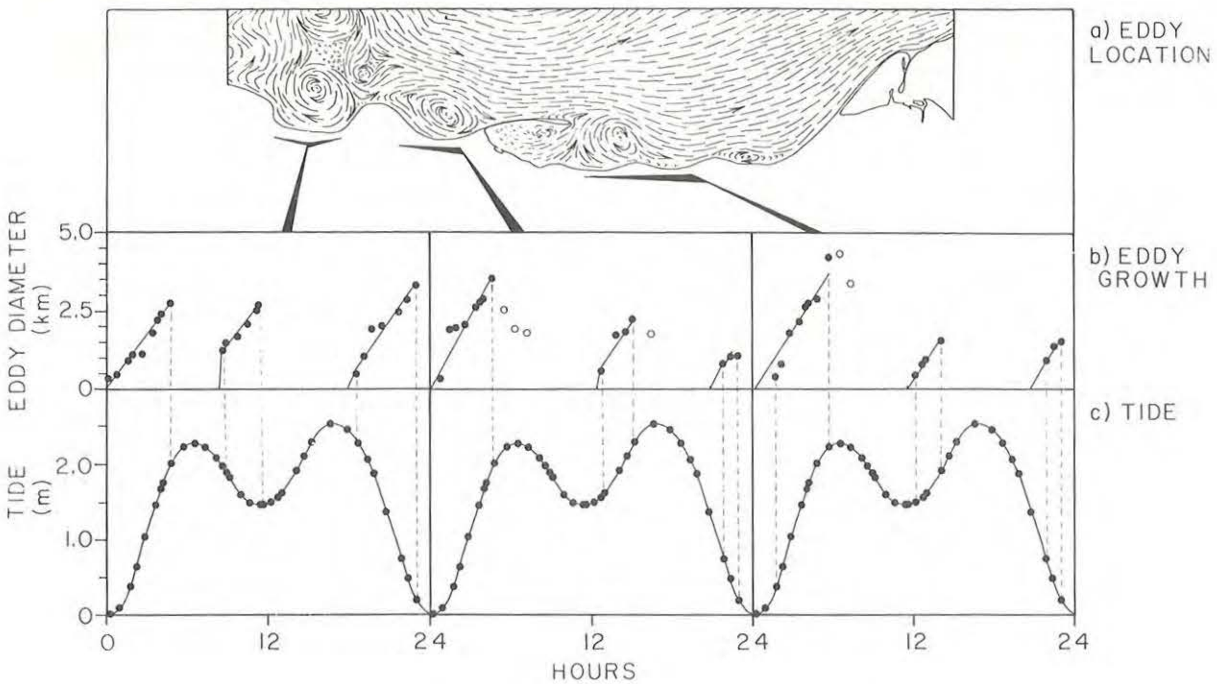

Figure 3.7. At three sites (a) growth of tidal eddies (b) in the hydraulic tidal model. Dots and circles denote respectively diameter during eddy growth and decay. In c) tidal phases are shown by dots on tide curves.

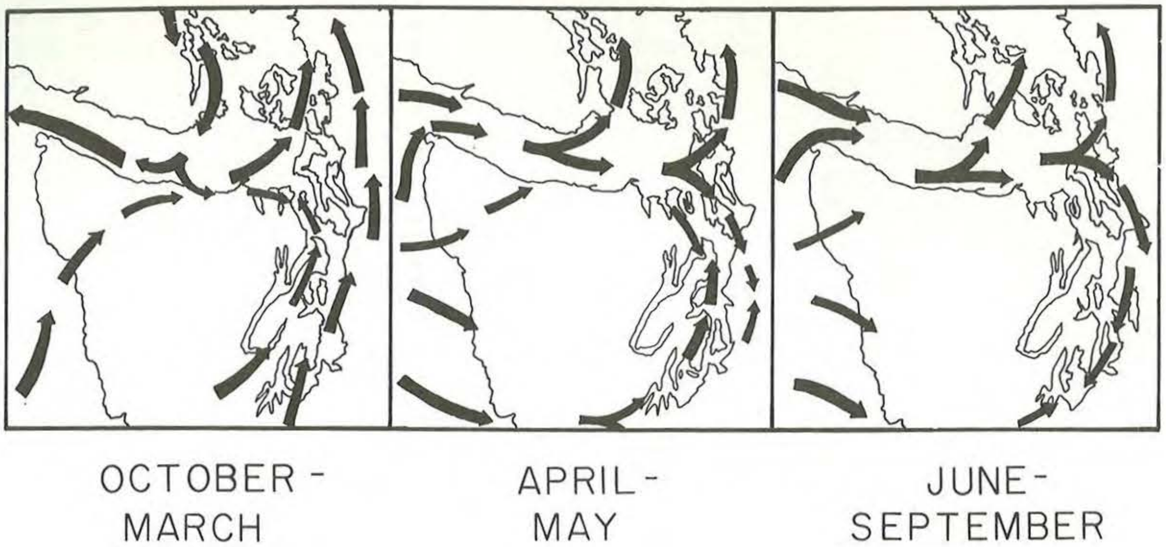

Figure 3.8. Seasonal progression of prevailing winds (adapted from Harris and Rattray, 1954). Note: arrows not to scale.

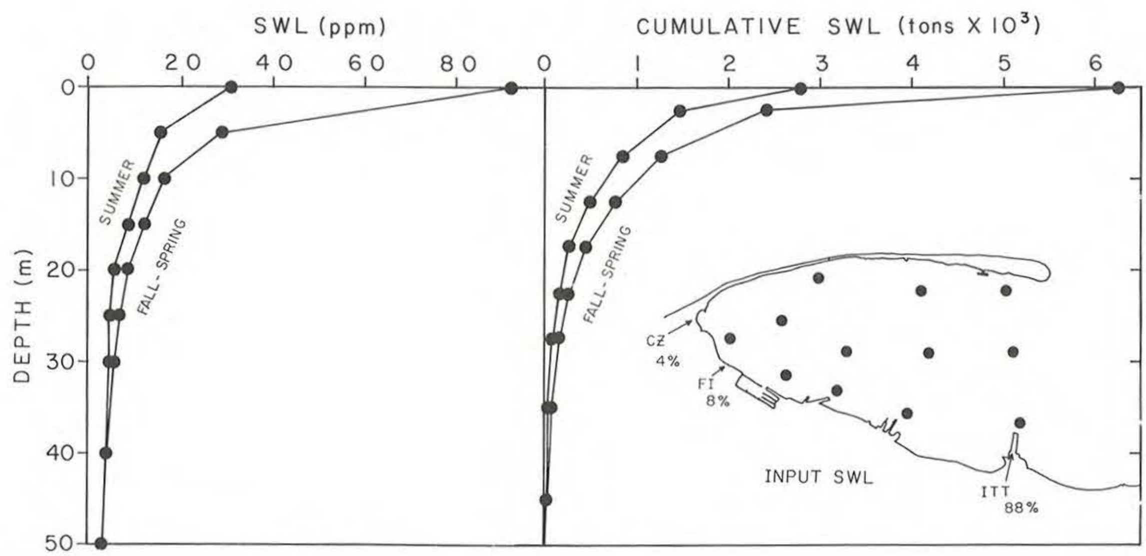

Figure 3.9. Seasonally averaged vertical profiles of the mean concentration (left) and cumulative amount (right) of sulfite waste liquor in Port Angeles Harbor (from Ebbesmeyer et al., 1979). Data from Callaway et al. (1965): summer, June-September, 1963; fall-spring, October 1963-January 1964 and February-April 1963. Inset shows locations of sampling stations and locations and percentages of SWL input. Notation: CZ, Crown Zellerbach, Inc.; FI, Fiberboard, Inc.; and ITT, ITT Rayonier, Inc.

hourly wind speed from the west (Fig. 3.10). Despite the difference in observational periods for winds (1947-1952) and SWL (1963-1964) there is an approximate inverse correlation between mean wind speed and total SWL. Thus winds are effective in transporting SWL eastward out of the Harbor.

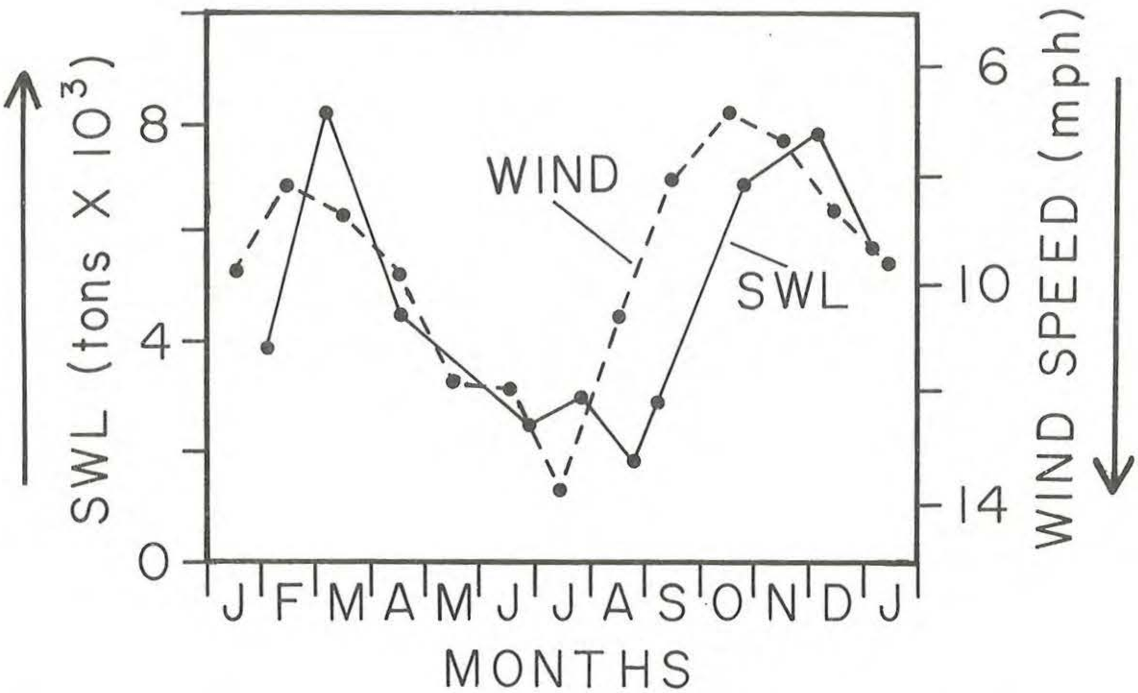

Figure 3.10. Comparison of seasonal cycles of mean hourly wind speed from the west and total sulfite waste liquor in Port Angeles Harbor (from Ebbesmeyer et al., 1979). Data: winds, 1947-1952 at U.S. Coast Guard Station; SWL, 1963-1964 at stations shown in Figure 3.9.

4. HARBOR RESPONSE

The response of estuaries to changes in material input can often be estimated using freshwater as a tracer. However the runoff into the Harbor and vicinity is small. Local rivers and creeks discharge annually approximately 2 km^3 whereas the rivers that empty into the Strait of Georgia and Puget Sound discharge annually approximately 150 km^3 and 40 km^3, respectively. Monthly average discharge for the Elwha River, Dungeness River, Morse Creek, and Siebert Creek are shown in Figure 4.1.

During the mid-1960's significant amounts of SWL were discharged into the Harbor at three locations by ITT, CZ, and FI mills (see Fig. 3.9). As a result there were a number of studies conducted to determine distributions of SWL and other water properties. These data can be used to estimate change in Harbor water properties with respect to those of exterior water.

4.1 SEASONAL CYCLES

Temperature, salinity, dissolved oxygen, and SWL were sampled at approximately one month intervals from February 1963 to January 1964 at a dozen locations in the Harbor and at a reference location approximately two kilometers north of Ediz Hook (Callaway et al., 1965). The values in the Harbor were averaged at the observation depths and the averages near surface and bottom in the Harbor were compared with those at corresponding depths at the reference station (Figs. 3.9, 3.10, 4.2, and 4.3).

Based on the monthly observations it appears that the measured natural variables (temperature, salinity, dissolved oxygen) in the Harbor closely follow those of exterior water in the Strait of Juan de Fuca. There are, however, some differences. Temperatures inside the Harbor were higher than the reference station during July-September. Local heating in summer is also evident in an infrared photograph of the Harbor (Fig. 4.4). During the remainder of the year temperatures were approximately equal inside and outside of the Harbor. Salinity inside the Harbor was higher than the reference station during January-March and lower during September-October. The oxygen concentrations are generally higher inside the Harbor during June-September and lower during the rest of the year.

4.2 RESIDENCE PERIOD

A useful measure of circulation is the mean residence period of a water parcel within a given volume of water. The residence period will vary signigicantly depending on the site of material input, stage of tide, and wind

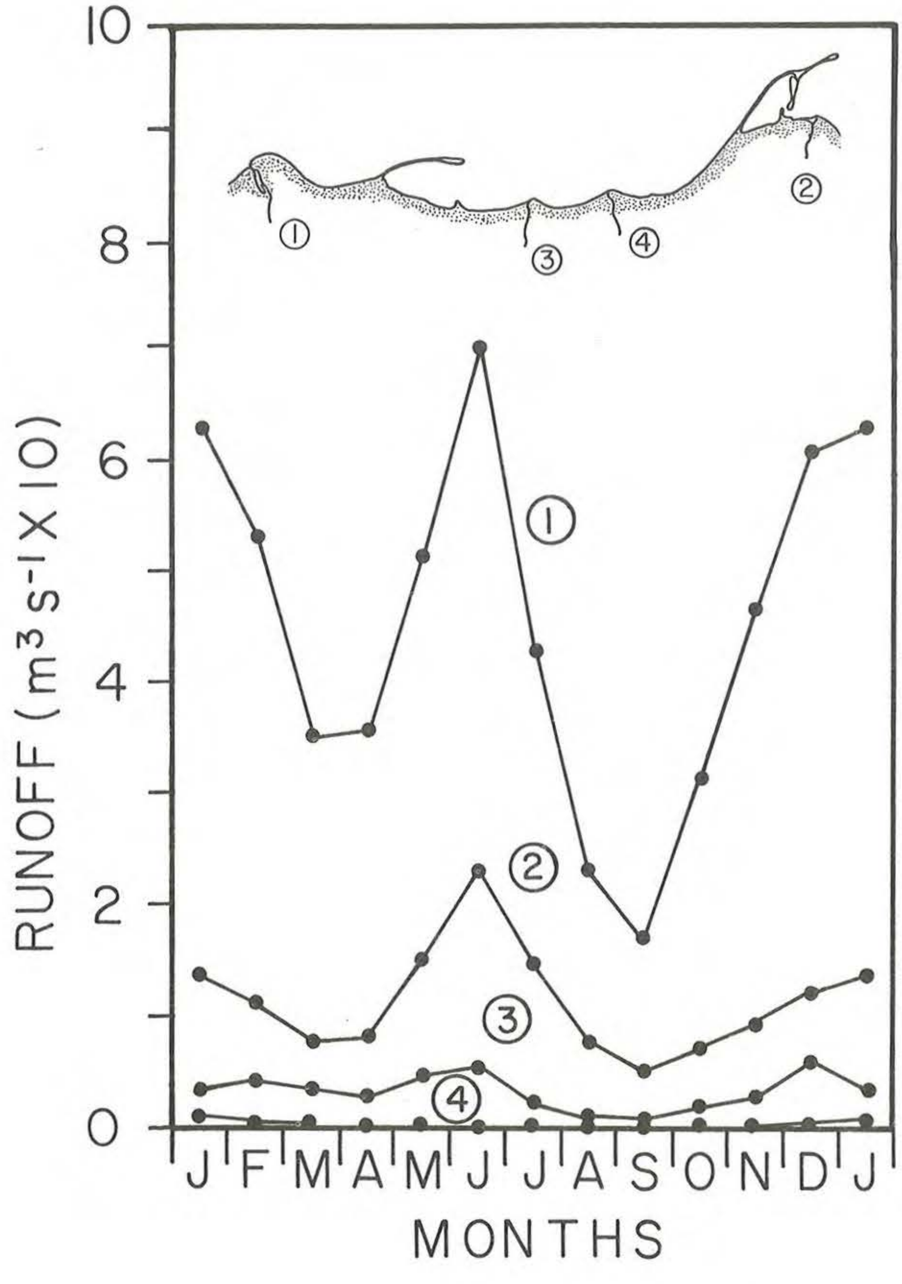

Figure 4.1. Seasonal cycles of runoff for: 1) Elwha River; 2) Dungeness River; 3) Morse Creek; and 4) Siebert Creek. See inset for locations.

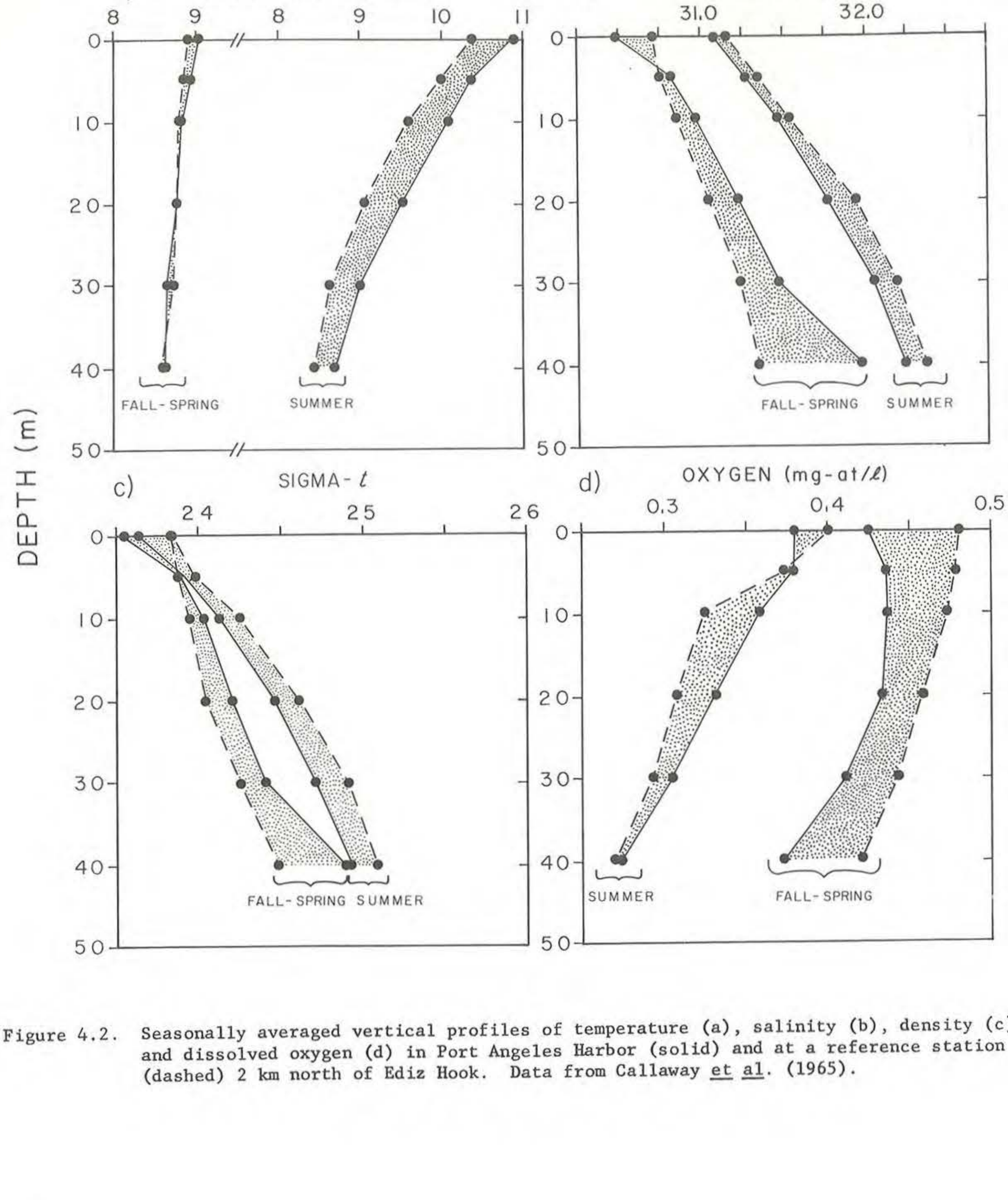

Figure 4.2. Seasonally averaged vertical profiles of temperature (a), salinity (b), density (c), and dissolved oxygen (d) in Port Angeles Harbor (solid) and at a reference station (dashed) 2 km north of Ediz Hook. Data from Callaway et al. (1965).

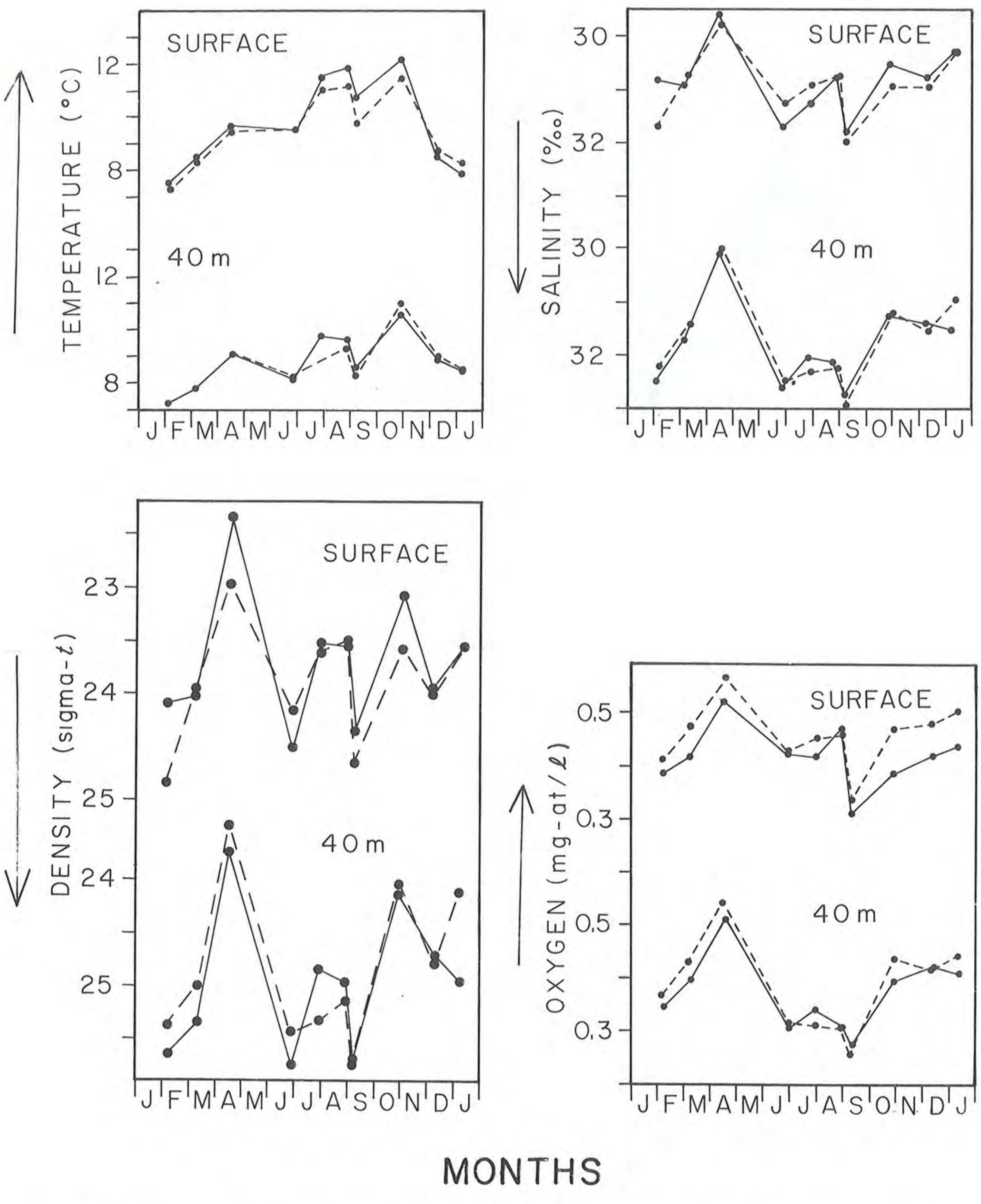

Figure 4.3. Seasonal cycles at surface and 40 m depth of temperature, salinity, density, and dissolved oxygen in Port Angeles Harbor (solid) and at a reference station (dashed) 2 km north of Ediz Hook. Data from Callaway et al. (1965).

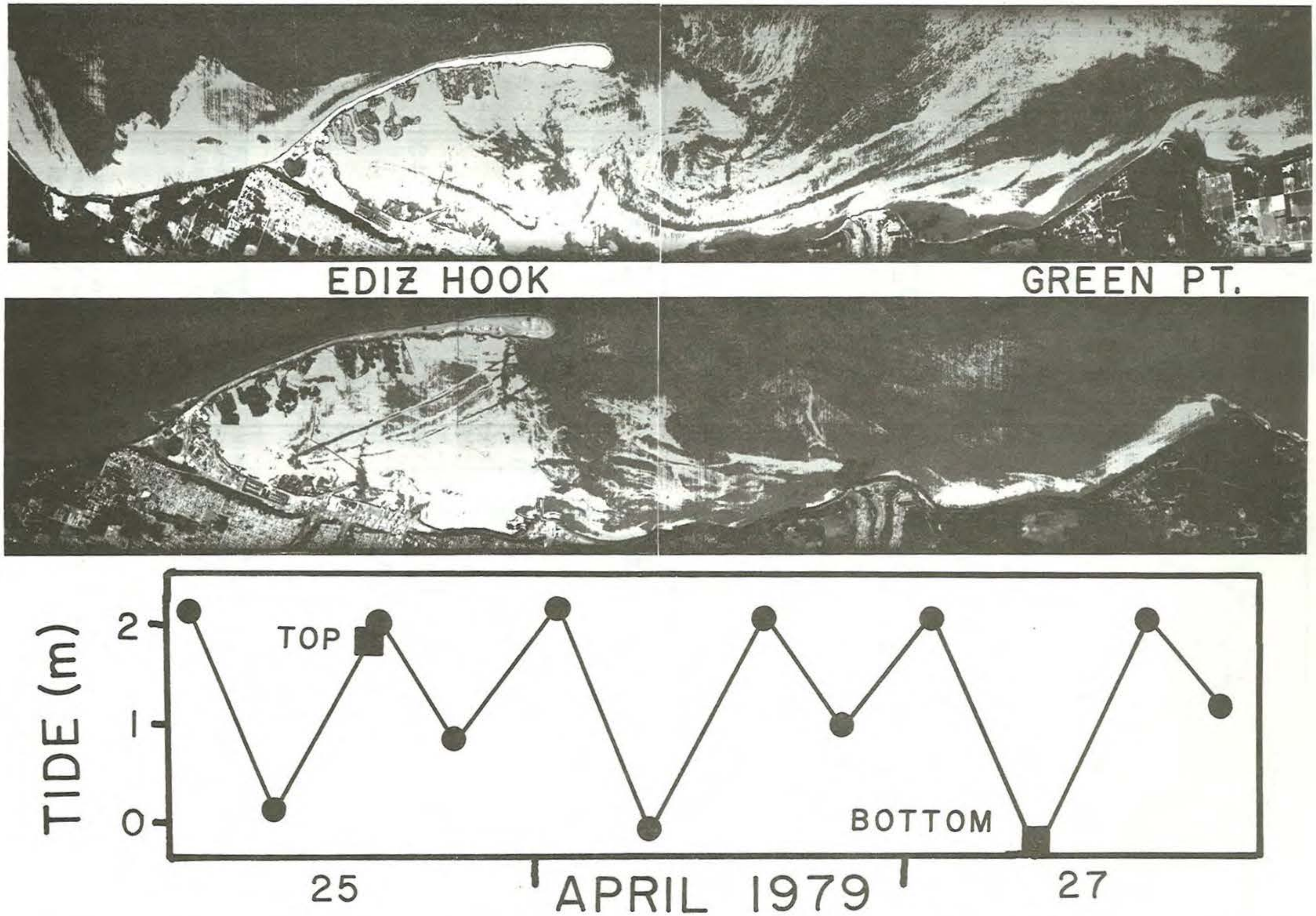

Figure 4.4. Black and white reproductions of infrared photographs taken in April 1979 by the Environmental Protection Agency. Lighter and darker areas denote warmer and colder temperatures, respectively. In the upper panel note the flood tidal eddies in the lee of Ediz Hook and Green Point.

condition. Actual particles of water cannot be followed using presently available technology. As a result two approaches have been used to estimate the mean residence period, as described below.

4.2.1 Input Changes of Sulfite Waste Liquor (SWL)

On several occasions there were abrupt changes in SWL discharges into Port Angeles Harbor. These resultant changes in SWL concentration within the Harbor can be used to estimate the residence period. Two occasions noted by the Washington State Pollution Control Commission (1967) are cited below.

Between 19 August and 3 September 1963 SWL was discharged only from the FI plant near the head of the Harbor. On 30 August effluent concentrations were measured. Assuming that all SWL in the Harbor was derived from the FI plant the mean residence period for SWL was 2 days, obtained as the total amount of effluent divided by the SWL input.

On 12 November 1964 SWL discharge into the Harbor abruptly decreased. During the following two weeks SWL concentration was measured near the surface at the head of the Harbor (Fig. 4.5). After four days the SWL concentration had decreased to small values.

4.2.2 Hydraulic Tidal Model Experiments

Two experiments were performed using the hydraulic tidal model in attempts to estimate the mean residence period. The first experiment consisted of timing the transit of a drift particle from a release site near the Harbor's head until the particle exited the Harbor's mouth. The particle was a plastic floatable bead having a diameter of approximately 3 mm (in the prototype this bead would measure 240 m in the horizontal by 4 m in the vertical). The transit time was measured ten times for releases all at lower-low-tide and a tide range of 2.6 m (from lower-low to higher-high tide as used in generating the tidal current patterns).

The result was a mean transit time of 4 days with a standard deviation of ½ day. In each trial the bead exhibited a meandering motion about a mean trajectory that exits the Harbor close to Ediz Hook. As the bead progressed eastward toward the mouth its speed tended to increase. The average speed from the release site to the Harbor mouth was approximately 0.012 m s^{-1}. This value is close to the mean eastward speed of 0.013 m s^{-1} recorded at 16 m depth at Site 1 (Appendix A.2) approximately on the bead's mean trajectory.

The mean residence period derived from the SWL observations apparently is smaller than that obtained from the tidal model experiment. Although the winds that occurred during the SWL observations were not available for this study, we speculate that the shorter residence periods for SWL resulted from westerly winds. These winds favor rapid removal of SWL that is concentrated near the surface.

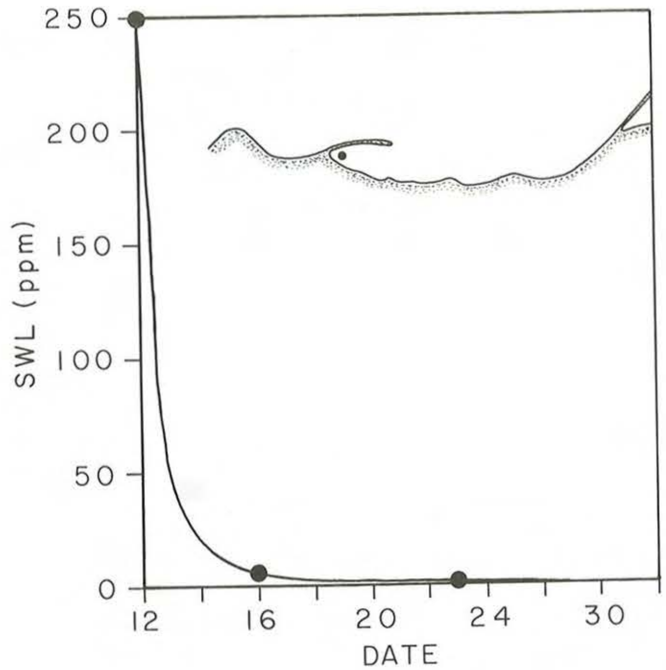

Figure 4.5. Concentration of sulfite waste liquor (dots) at the head of Port Angeles Harbor (inset) after abrupt decrease in effluent discharge on 12 November 1964 (from Ebbesmeyer et al., 1979).

The first model experiment was performed in the near-surface layer. An estimate of the residence time for the Harbor's overall volume can be obtained as the Harbor volume divided by the tidal volume between successive high and low tides. This computation gives the minimum number of flood tides that are required to replace the Harbor water volume. The result is 9 flood tides for spring tides used in the model experiment; 10 tides for the diurnal tidal range (see Table 1.1); and 17 tides for the mean tidal range in the Harbor. Since there are usually two flood tides per day, the residence period expressed in days will be smaller than the residence period expressed in number of tides. The result from the model experiment suggests that the residence period in days is roughly equivalent to half of the estimates as expressed in flood tides; i.e., the mean residence periods for the diurnal and mean tidal range is about 5 and 9 days, respectively.

In the second experiment the Harbor was filled with dye --- a week later most dye evident to the unaided eye had escaped the Harbor, except for some that remained below sill depth.

From the foregoing computations and experiments primarily near the surface, it is concluded that the mean residence period in the upper layer varies from approximately a day to a week depending on the time and site of release. Residence periods appear to increase toward the head of the Harbor. The available measurements are insufficient to determine the residence period in the deeper layers particularly below sill depth.

4.3 NET CIRCULATION

The two previous model experiments suggest that the tides may induce a weak net circulation at least in the surface layers of the Harbor. This is to be expected in a region of strong tidal currents and complex bathymetry. The phenomena has been commonly termed tidal pumping, and according to Bowden (1978) it is "the name given to the effect of a residual tidal flow, varying across the estuary, arising from the interaction of the tidal wave with the bathymetry." In order to identify particular features of bathymetry associated with tidal pumping, beads were released at a variety of sites and tidal ranges in the model within the Harbor. The result was that irrespective of release site or time the beads meandered toward Ediz Hook where they were rapidly discharged from the Harbor.

The results from the hydraulic model experiments and currents measured at Site 1 (Fig. 3.2) indicate a weak net flow toward the Harbor mouth. In six previous studies the mean circulation near the surface has been reported. In three studies it was concluded that there was a net counterclockwise circulation within the Harbor (Stein et al., 1963; Washington State Pollution Control Commission, 1967; and EPA, 1974). In two reports flows have been described as being predominantly north or south across the Harbor mouth associated with a tidal eddy located east of the Harbor (Charnell, 1958; Tollefson et al., 1971). They gave no pattern of net circulation within the Harbor. Finally in one study a net flow directed east by northeast was determined for a site near the southern shore of the Harbor's mouth (Stein and Denison, 1966). The conclusion of these six reports were based primarily on SWL patterns and supplemented by short period current meter and drogue observations.

We conclude that patterns of net circulation in the Harbor cannot be determined based on presently available data. The mean flow is undoubtedly weak at most locations in the Harbor. The transients of wind speed and direction have pronounced effects near surface. On short time scales wind effects are variable and this may explain the conflicting reports of surface circulation patterns that were based primarily on SWL concentrated near the surface. Moreover the vertical profile of mean flow remains undetermined. Long time series of current measurements taken concurrently at various depths and locations will be required to deduce the net flow patterns.

5. DISPERSION OF MATERIAL INPUTS

The effects of winds and the mean countercurrent favor eastward transport near the shore while tidal eddies provide lateral dispersion of materials to both offshore and nearshore regions. Some aspects of the transport and dispersion are illustrated in the movement of several materials that have been observed in the study area. These include materials from natural sources and man's activities both accidental and deliberate.

5.1 OIL SPILL

On 13 May 1979 an oil spill occurred near the Harbor mouth at lower-low water during a period of spring tides (Fig. 5.1). Aerial photographs were taken about a day later at mid-stage during a major flood tide. The winds during this period were mostly calm with occasional reports as high as 3 m s^{-1}. The photographs showed that slicks and sheens had spread in patches to the westward end of the Harbor as well as offshore and westward outside the Harbor.

5.2 SUSPENDED SEDIMENT

The rivers and creeks that discharge at the local promontories at times carry significant loads of suspended sediment. In the marine water the sediment is evident as plumes that begin at the promontories and spread offshore. An example is shown in Figure 5.2. The sediment can be seen a significant distance both offshore and along the shore to the east in this instance.

Since the installation of dams on the Elwha River sediment is trapped upstream that once was discharged into the Strait of Juan de Fuca. In 1930, the construction of a water supply line and protective rock covering along the base of the cliffs west of Ediz Hook to the Elwha River further reduced sediment input to marine waters from cliff erosion. According to the U.S. Army Corps of Engineers (1971), before these installations Ediz Hook apparently was in a state of equilibrium or growth, adding as much or more new sediment as was lost each year. Since 1930 the Hook has been in an "active state of erosion due to lack of adequate feed material" (U.S. Army Corps of Engineers, 1971) indicating the Elwha River and cliff sediments to be previously the major sources for Ediz Hook. These sediments have been carried a significant distance alongshore eastward and it is likely contaminant materials released near shore would exhibit a similar behavior. This may be seen in the patterns of pulp and paper mill effluents.

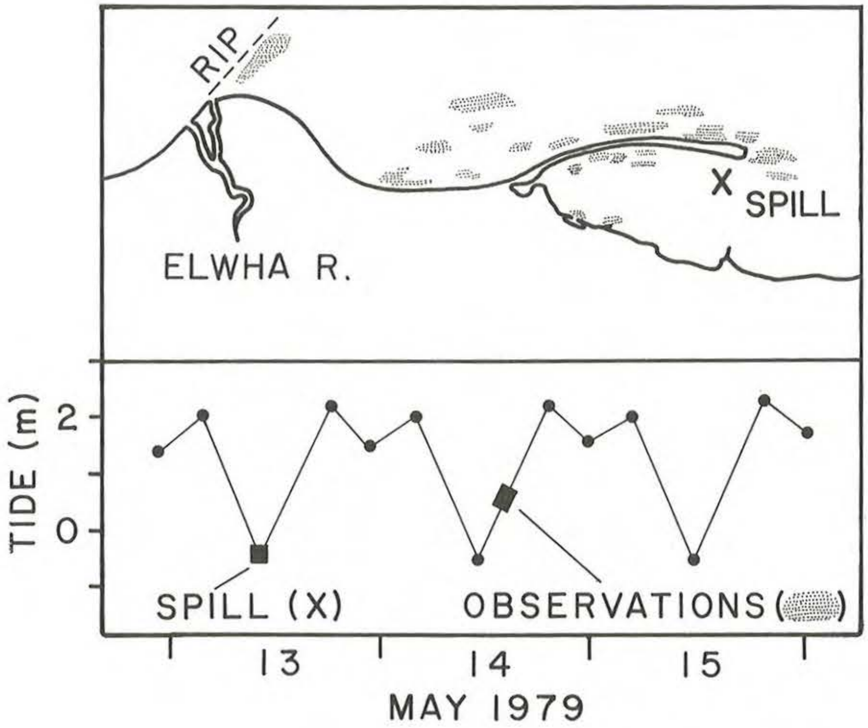

Figure 5.1. Dispersion of oil from a spill (X) on 13 May 1979 as observed (stippled) 14 May 1979. Notation: RIP, rip line associated with Elwha River discharge.

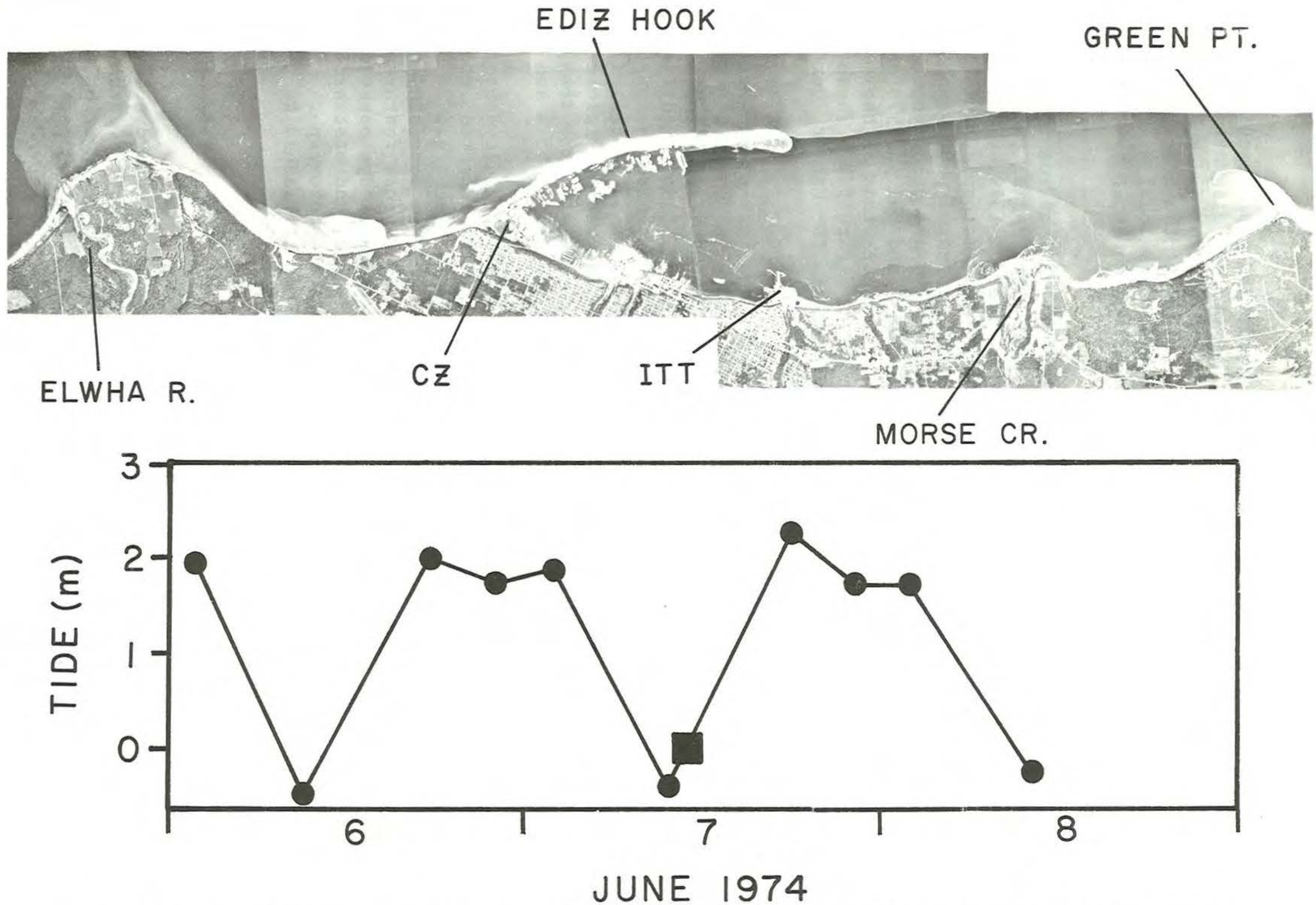

Figure 5.2. Aerial photograph showing sediment plumes of local rivers and creeks (1974). Source: U.S. Army Corps of Engineers. Square on inset shows time of photograph and tidal phase. Notation: CZ, Crown Zellerbach, Inc., and ITT, ITT Rayonier, Inc.

5.3 PULP AND PAPER MILL EFFLUENT (SWL)

By industrial standards the production of pulp and paper requires large volumes of water (see Hutchins, 1979). The average discharge per year (1966-1978) for ITT and CZ are approximately 0.051 km^3 (37 mgd) and 0.01^2 km^3 (9 mgd), respectively. Although the volume of the receiving water for effluent is large compared with discharge from local mills, effluent patches can persist for considerable periods as shown by detailed field studies in Puget Sound (Bendiner, 1976).

With the proper lighting and wave conditions the ITT effluent is often apparent by visual observation and in infrared and color aerial photographs. Visual observations of the effluent were made in 1978 and 1979 by EHI from an aircraft positioned with an accurate ranging system (Motorola Mini Ranger III; ± 30 m accuracy as used aboard the aircraft). Infrared photographs of the effluent were obtained by the EPA in 1974 and 1979, and color photographs were obtained by the EPA in 1974, ITT in 1976, and EHI in 1978 and 1979 as listed in Appendix A.5. Representative configurations of the effluent on slack, ebb, and flood tides are shown in Figure 5.3. These patterns show that the effluent has been visible within the Harbor, north of Ediz Hook, and eastward to Green Point, respectively.

More sensitive indicators of the effluent that show its areal extent are the Pearl-Benson Index (PBI) and oyster bioassay toxicity tests. The concentration of effluent is expressed by the PBI. The PBI data used in the present study were determined using the Barnes et al. (1963) modification of the Pearl and Benson (1940) technique. PBI is expressed as parts per million (ppm) by volume. The toxicity of the effluent is expressed by percentage oyster larvae abnormality as determined using methods initially developed by Woelke (1968). The areal extent of the effluent from these results in both cases reaches eastward to Dungeness Spit (Figs. 5.4 and 5.5).

For comparison with aerial, PBI, and oyster bioassay toxicity observations of pulp mill effluent, photographs were taken of dye injected into the hydraulic tidal model at the sites of the ITT and CZ discharges (Fig. 5.6). Spring tide conditions were simulated. The dye consisted of a mixture of Sheaffer Eaton blue ink and freshwater. The gross features of the dye and effluent patterns are similar. In both cases dye penetrated to the head of the Harbor, westward beyond the study area, and eastward beyond Dungeness Spit where the dye became too dilute to photograph. Visual observations of the dye in this area showed that it reached to the mouths of Sequim and Discovery Bays.

5.4 DRIFT SHEETS AND CARDS

The general patterns indicated by effluent observations and dye injections are consistent with the trajectories of drift sheets and cards that were released into the Harbor and its approaches by Ebbesmeyer *et al.* (1978, Figs. 5.7 and 5.8). From a total of 123 released drift sheets 43% were recovered on the western shores of Dungeness Spit and its approaches. From a total of 700 released drift cards 240 were recovered onshore.

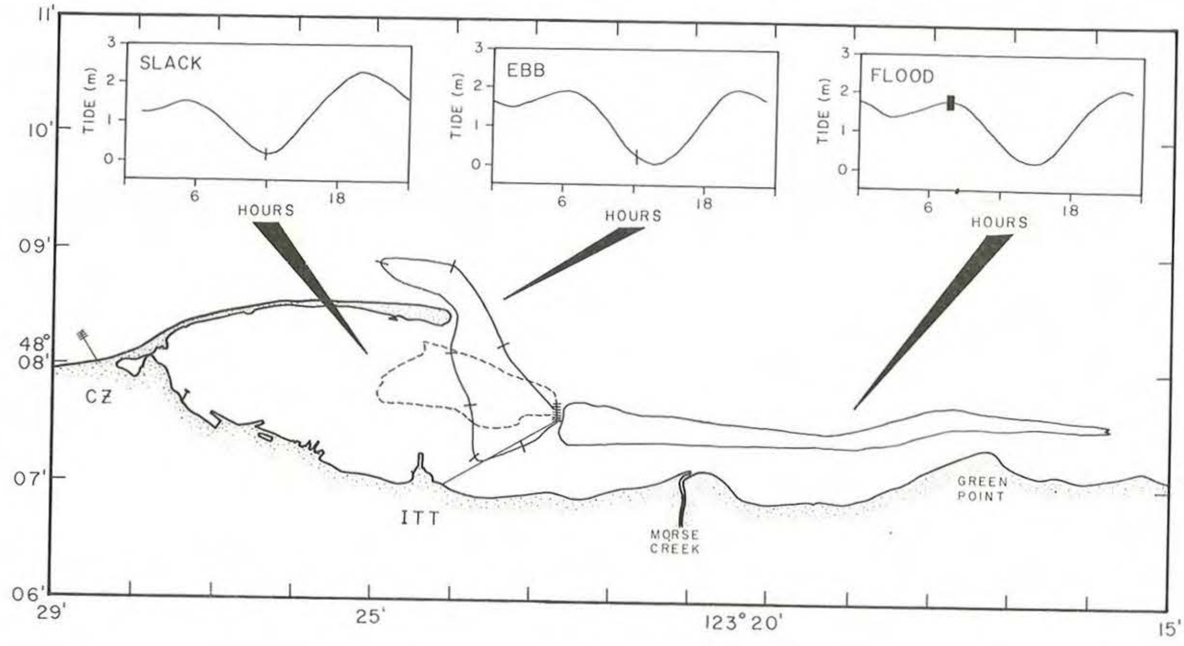

Figure 5.3. Slack, ebb, and flood patterns (left to right) of effluent from the ITT Rayonier, Inc. outfall (from Ebbesmeyer et al., 1979). Data: slack pattern (dashed) on 17 June 1976 from Fagergren (1976); ebb and flood patterns (solid) on 29 and 30 April 1978, respectively, from data on file at Evans-Hamilton, Inc. Observations at times of ticks on tidal phases (inset).

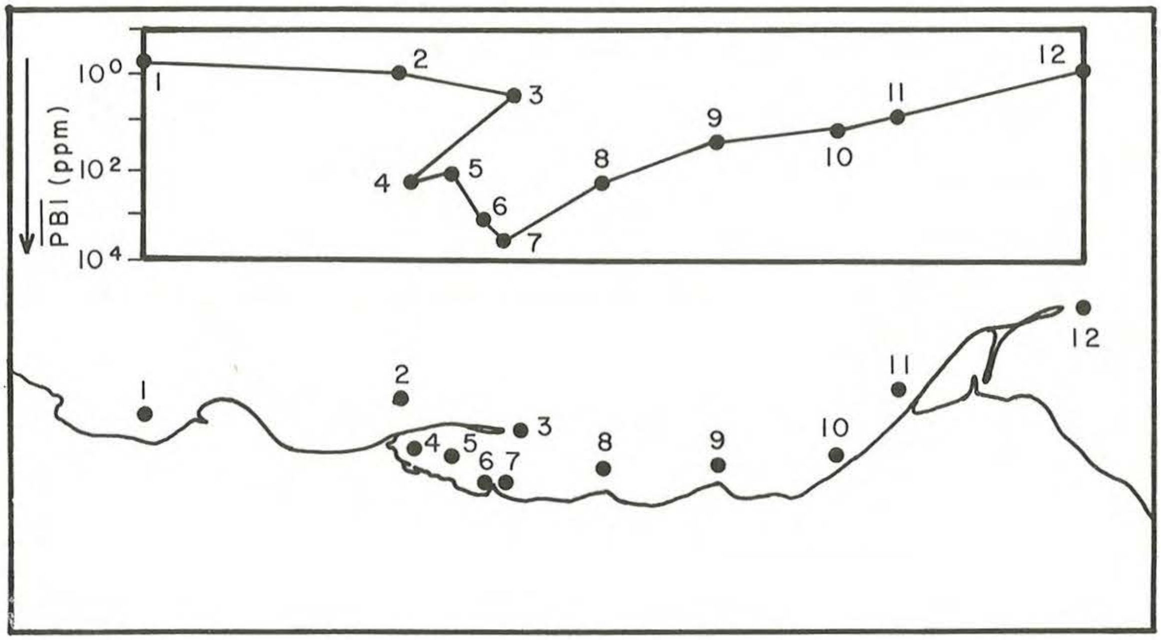

Figure 5.4. Mean concentration (top) of sulfite waste liquor (Pearl-Benson Index) at selected stations along the shore (numbers, bottom; from Ebbesmeyer et al., 1979). Data: 1963-1965 from page 444 of Washington State Pollution Control Commission (1967).

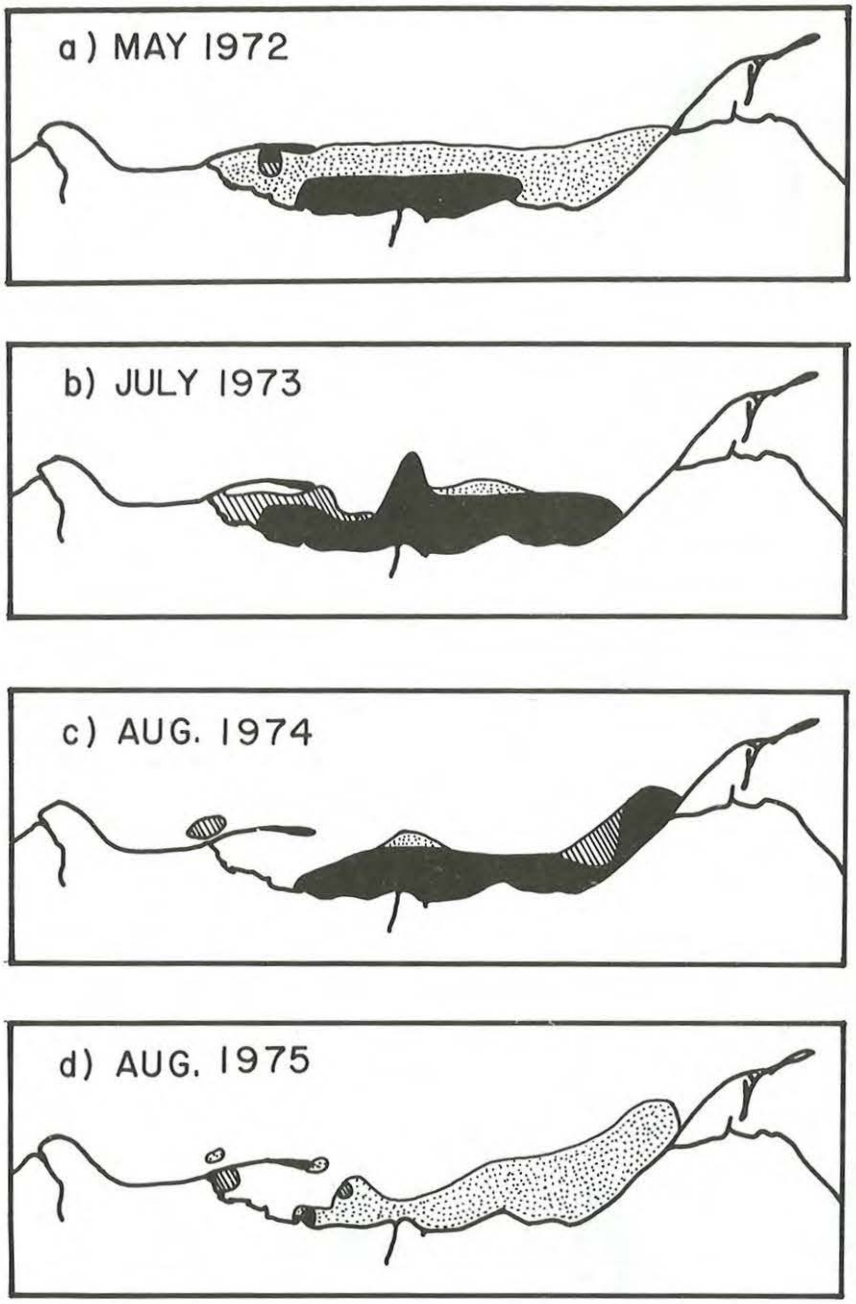

Figure 5.5. Oyster larvae bioassay tests of effluent toxicity on four occasions (a-d; from Cardwell et al., 1977). Notation: stippled, greater than 5% abnormality; hatched, greater than 20% abnormality; and blackened, greater than 50% abnormality.

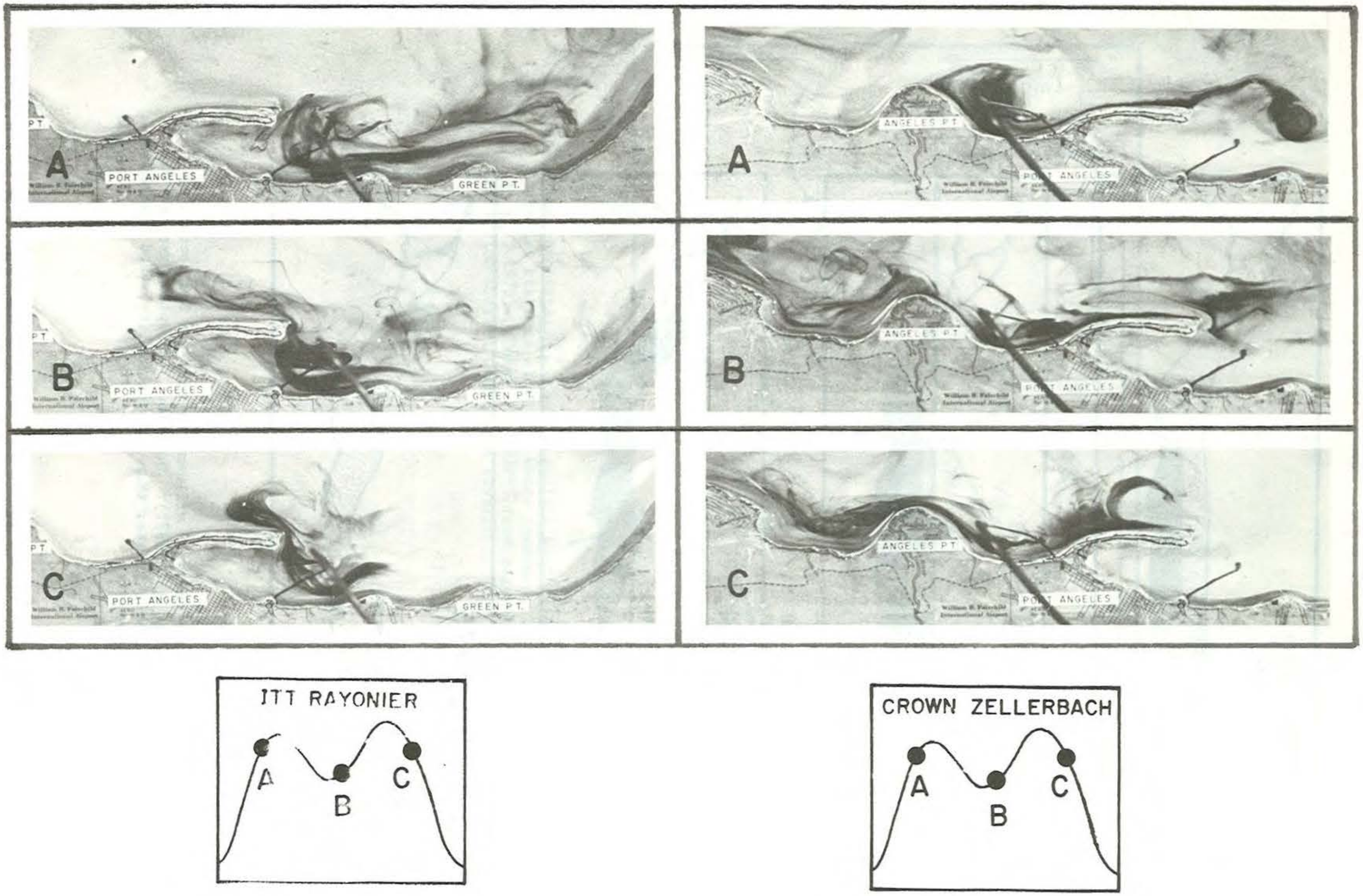

Figure 5.6. Photographs of dye injected into the hydraulic tidal model at ITT Rayonier, Inc. and Crown Zellerbach, Inc. outfall locations (adapted from Ebbesmeyer <u>et al</u>, 1979). Insets at bottom show tidal phases.

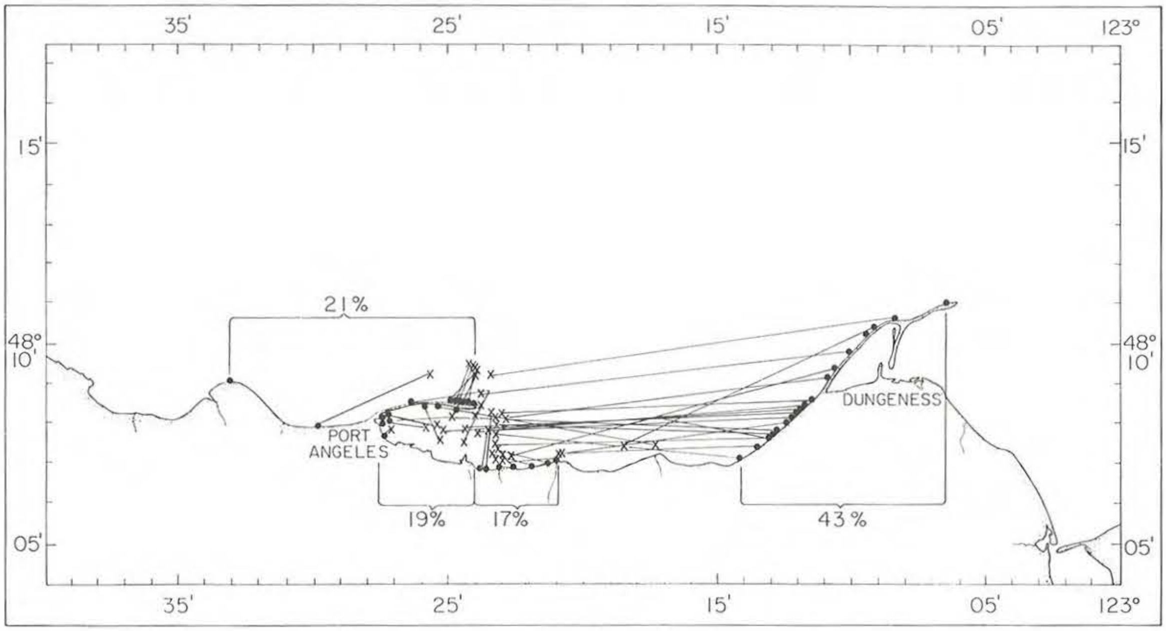

Figure 5.7. Recoveries onshore of drift sheets released in Port Angeles Harbor and approaches expressed as percentage of 42 recoveries (from Ebbesmeyer et al., 1978). Notation: X, launch site; and dots, recovery positions.

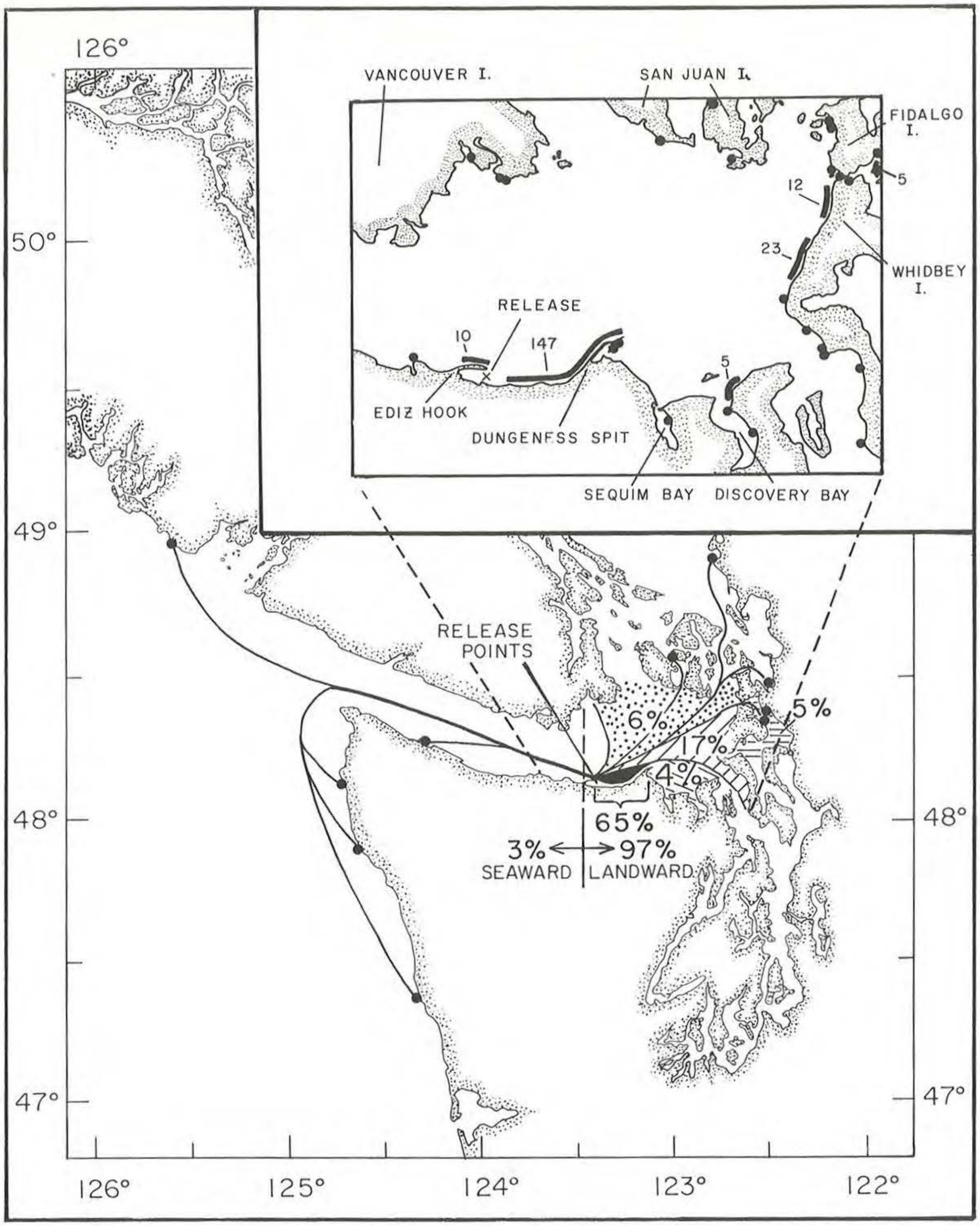

Figure 5.8. Recoveries onshore of drift cards released in Port Angeles Harbor expressed as percentage of 240 recoveries (adapted from Ebbesmeyer et al., 1978). Notation: dots, single recoveries; stippling, hatched, and blackened areas, multiple recoveries expressed as percentages of total recoveries. Inset shows the number of recoveries in the inner Strait of Juan de Fuca.

Of the recoveries 3% drifted westward of the Harbor and 97% drifted eastward, where 65% were found from Ediz Hook to Dungeness Spit; 4% in Sequim and Discovery Bays and inside Dungeness Spit; 17% on the westward shores of Whidbey Island; 5% inland of Deception Pass in Whidbey Basin; and 6% on Fidalgo, Vancouver, and the San Juan Islands. Similar pathways of drift cards have been reported by Pashinski and Charnell (1979) although they do not give percentage recoveries by area.

The recoveries of drift cards on the north and south shores of Dungeness Spit are of particular concern because of the National Wildlife Refuge located there. Cox et al. (1978) observed some drift sheet movements that provide insight as to the pathways in which contaminants can be transported toward and around Dungeness Spit. They noted a tendency for drift sheets to collect among localized patches. A large patch occurred just to the north of Dungeness Spit (Fig. 5.9). After several days approximately 20 drift sheets had converged from a distance of 30 km into a prominent patch. Other drift sheets showed southward movement toward the shore east of Dungeness Spit (Fig. 5.10). These observations as well as mean currents obtained from several deployments of moored current meters, recoveries of drift cards by Ebbesmeyer et al. (1978), and recoveries of drift cards by Pashinski and Charnell (1978), indicate a pathway around Dungeness Spit and from offshore toward the more confined waters of Sequim and Discovery bays and their approaches.

In order to illustrate the tidal flow eastward around Dungeness Spit photographs were taken of the hydraulic tidal model. Figure 5.11 shows a streak photograph of a tidal eddy that develops on flood tides in the lee of Dungeness Spit. Material inputs can be transported by this eddy into the waters behind Dungeness Spit as shown by dye injected into the model (Fig. 5.12). As mentioned earlier dye reached the mouths of Sequim and Discovery bays, as well as the protected waters behind Dungeness Spit.

The drift card recoveries also indicate that an oil spill in the Harbor and its approaches will be transported over a wide area to the shores of the inner Strait of Juan de Fuca, Puget Sound, and the Strait of Georgia. In addition there are several pathways in which materials can be transported inland at depth.

5.5 CONTAMINANT PATHWAYS INLAND AT DEPTH

Observations of recent oil spills from the grounding of the tanker AMOCO-CADIZ off France (see Galt, 1978) and the blowout of the IXTOC I well off Mexico (see Botzun, 1979; Oil Spill Intelligence Report, 1979) have suggested that oil may be transported in quantity beneath the water surface. In this section we discuss some routes by which oil introduced at surface in the Strait of Juan de Fuca may be carried at depth into Puget Sound and the Strait of Georgia.

In the highly turbulent and constricted entrances such as the Green Point-Victoria sill, Admiralty Inlet, and passages in the San Juan Archipelago, surface and bottom waters are vigorously mixed. The tidal mixing

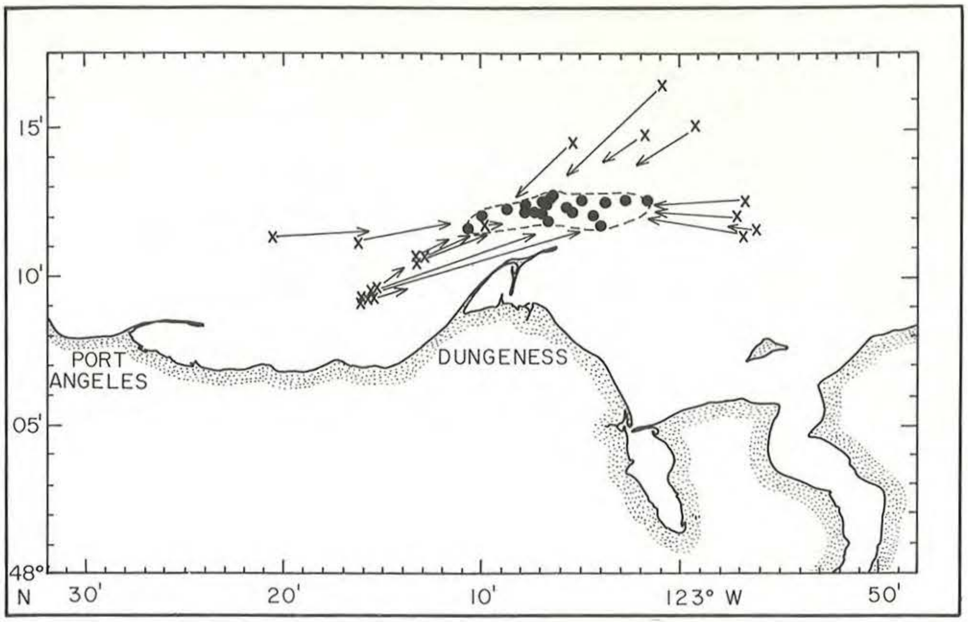

Figure 5.9. Convergence of 20 drift sheets into a patch off Dungeness Spit. Data from Cox et al. (1978). Notation: X, launch positions; arrows, net direction of movement; and dots, positions of drift sheets at 1200-1500 on 26 August 1978.

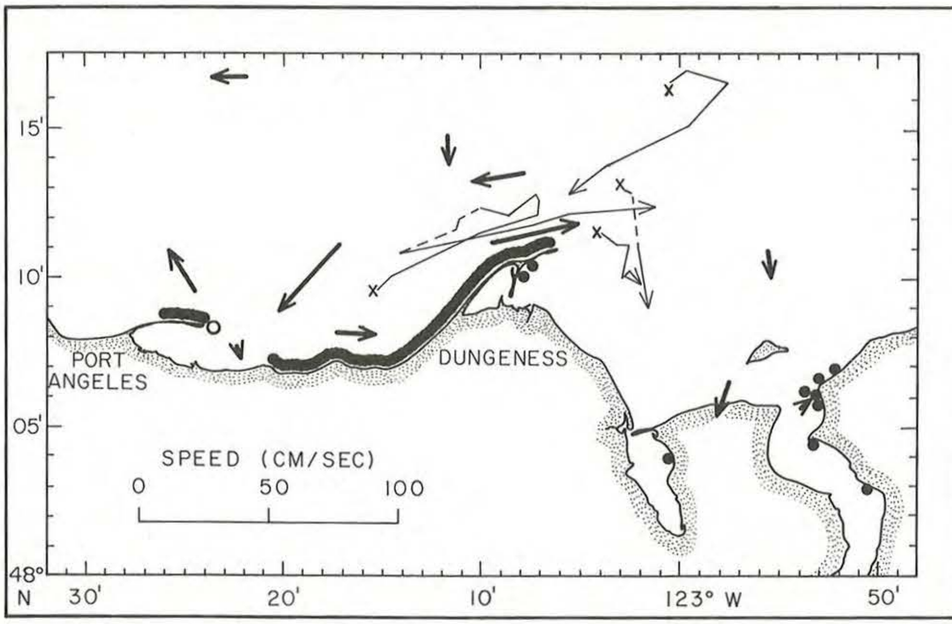

Figure 5.10. Selected trajectories of drift sheets, recoveries of drift cards, and net currents from Port Angeles Harbor to Sequim and Discovery Bays. Notation: X and connecting solid and dashed lines, drift sheet launch positions and observed and interpolated trajectories, respectively; dots and solid lines alongshore, single and multiple drift card recoveries, respectively; and bold arrows, net currents near the surface (approximately 5 m depth) from longer period current meter records. Data: drift sheet trajectories, Cox et al. (1978); drift card recoveries, Ebbesmeyer et al. (1978); and net currents, Cannon (1978). Speed scale applies only to net currents.

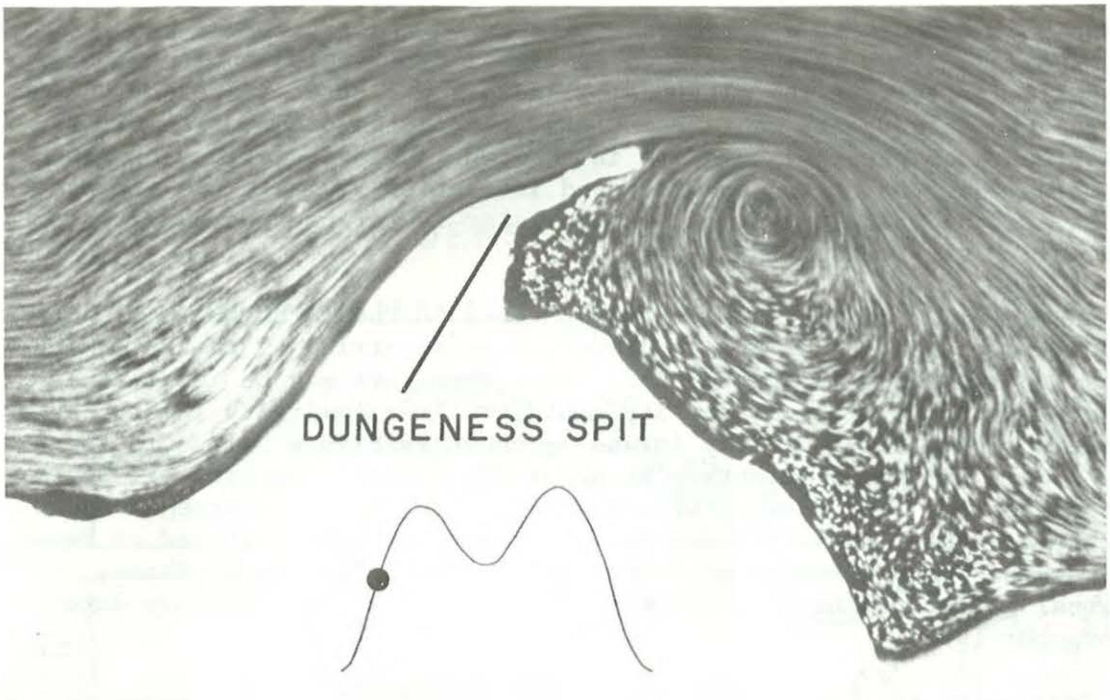

Figure 5.11. Streak photographs of a tidal eddy in the lee of Dungeness Spit in the hydraulic tidal model. Dot on inset shows tidal phase of streak photograph.

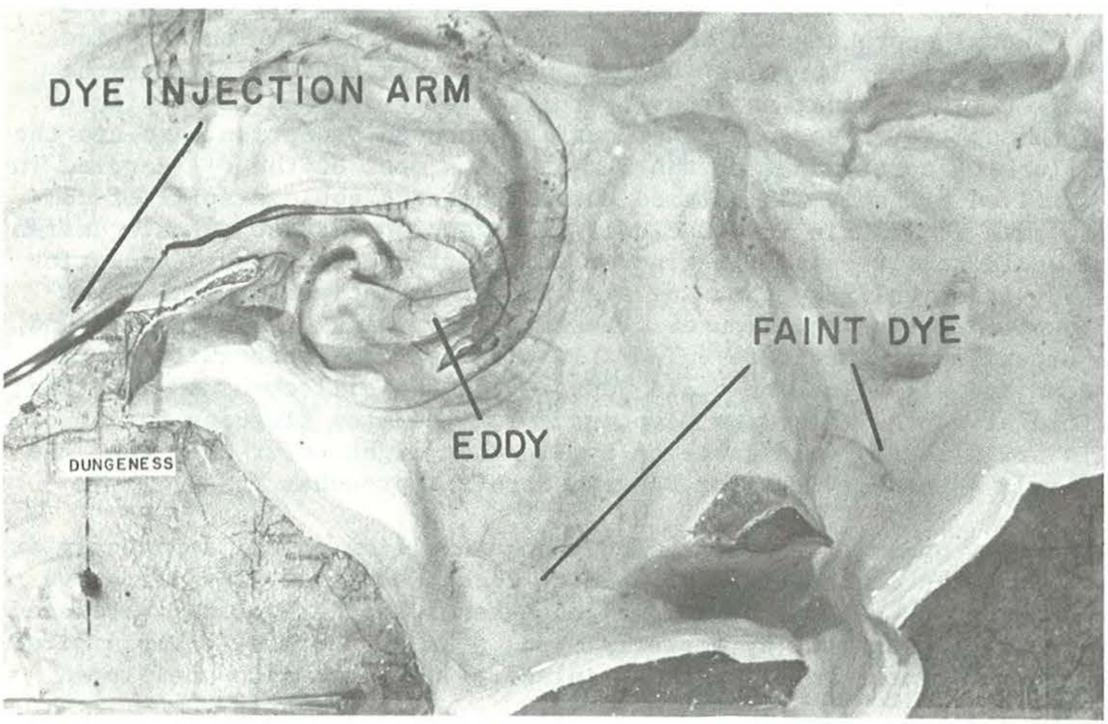

Figure 5.12. Photograph of dye in the hydraulic tidal model. Inset of Figure 5.11 (above) shows tidal phase.

results in numerous rip and frontal zones at the water surface where floatable materials often collect (based on visual observations by the authors from small aircraft at low altitude). These zones often represent the convergence of two currents where one sinks beneath the other. The mixing of surface and deep waters is evident in the longitudinal sections of water properties near the bottom as discussed in section 3.2. In the mixing process a significant amount of surface water is refluxed downward into the lower layer that flows inland.

In a similar pathway, oil at the surface in the turbulent sill zones may be partly emulsified, and/or dissolved, and carried by the refluxing process to mid-depth in Puget Sound. This transport may be imagined as following contours of equal density southward from Admiralty Inlet. As an example a hypothetical pathway inland is shown in Figure 5.13. In Puget Sound's Main Basin and tributary branches the finely dispersed oil particles may coalesce and rise slowly to intermediate density interfaces and accumulate there. An illustrative example for the process as observed at Deception Pass has been provided by Professor Emeritus Clifford A. Barnes (personal letter to the State of Washington Department of Ecology dated 26 November 1974):

"Following the 1971 spill of Number 2 diesel oil at the Texaco refinery dock near Anacortes, University of Washington personnel operating a laboratory on Kiket Island noted diesel oil odor in seawater pumped into the Laboratory from a subsurface intake. No oil slick was seen on the surface of the bay. The probable sequence is that some of the oil ebbing from Guemes Channel south through Rosario Strait was carried by the ensuing flood through highly turbulent Deception Pass. It then carried in the more saline influx under an interior low salinity surface layer without rising through it. Due to the net outflow through Deception Pass and the rapid flushing northward from the Skagit Delta most of the oil carried inward of flood probably was carried out on the next ebb. A spill of comparable size in Rosario Strait closer to Deception Pass at certain current phases would have resulted in greater inward transport through Deception Pass, but it is unlikely that any significant amount would reach Puget Sound proper through this route. The Admiralty Inlet - Main Puget Sound Basin situation is much more vulnerable owing to close proximity of the very deep and slow flushing basin just inside the sill combined with the net flood at depth. Likewise deep waters of the slow flushing Strait of Georgia are directly vulnerable to spills that might occur in either the Haro Strait - Boundary Pass or Rosario Strait approaches."

The flow dynamics necessary for the downwelling of oil apparently exist in the energetic inner Strait of Juan de Fuca. Moreover, the effective region from which oil may be downwelled extends farther westward because of the surface transport by westerly winds. Except for the example cited by Professor Barnes the oil pathway inland at depth remains unexplored.

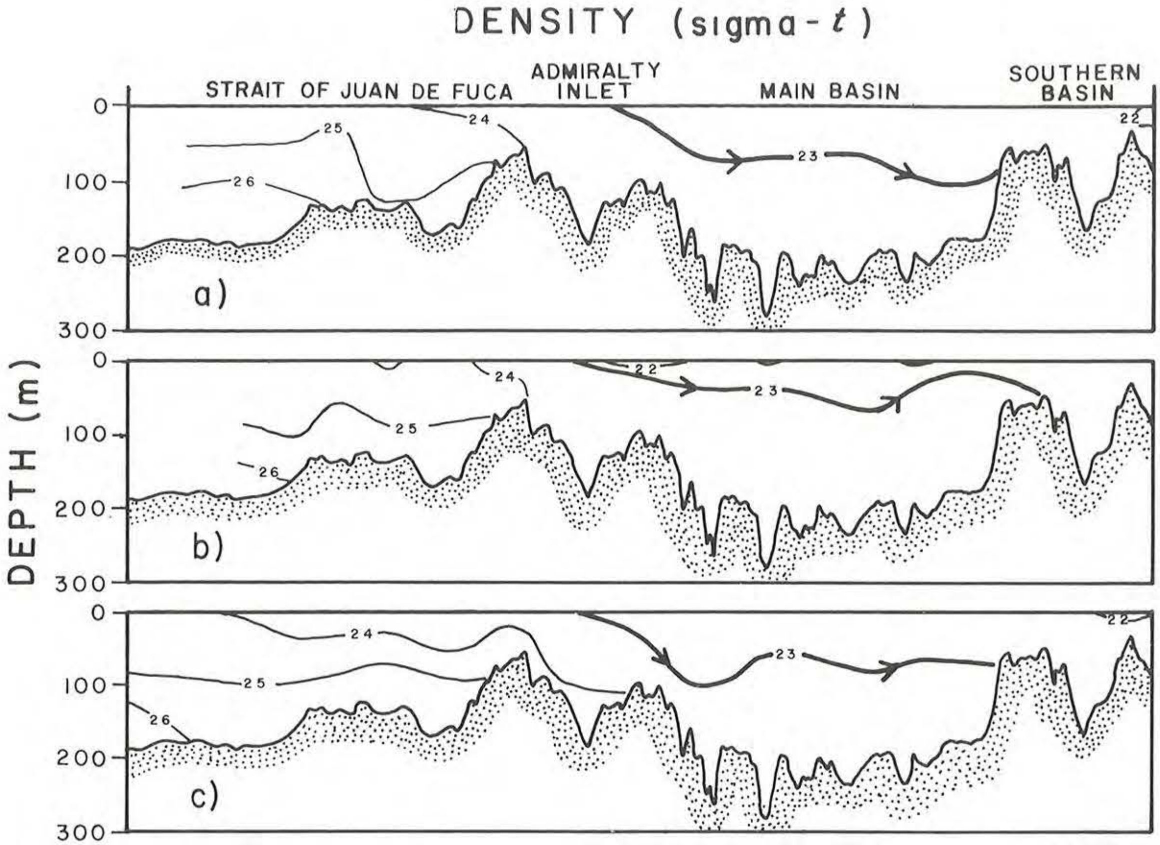

Figure 5.13. Profile view of density (expressed in sigma-t units) at mid-channel from the inner Strait of Juan de Fuca to Puget Sound's Main Basin (adapted from Collias et al., 1974). Heavy lines with arrowheads denote possible pathway at depth of oil transport into Puget Sound. Dates: a) 15-17 Septemper 1958; b) 19-21 November 1958; and c) 19-23 December 1958.

5. SUMMARY AND CONCLUSIONS

Port Angeles Harbor is a major shipping port located on the northern coast of Washington. Recently there has been concern about the fate of petroleum that might be spilled in the Harbor and its approaches as a result of proposed tanker routes and offloading facilities. This report presents a synthesis of historical oceanographic data collected during 1932-1979 in and near the Harbor. Emphasis is placed primarily on the circulation near the water surface and its effects on the transport and dispersion of spilled oil.

Although there exists a considerable body of historical data most of it has not been previously examined within a single framework. The data are scattered in numerous reports and unpublished compilations. Where possible, original data were obtained and analyzed. The data base examined included observations of tides, currents, winds, runoff, water properties, and transport of two previous oil spills, suspended sediment, and pulp mill effluent. In order to provide the continuity in time and space that is necessary for an adequate synthesis of the data, a hydraulic tidal model was constructed of the eastern Strait of Juan de Fuca. The model was compared with observed water movements and it was concluded that surface tidal currents associated with shoreline irregularities were adequately portrayed. Favorable comparisons were also found between patterns of dye injected into the model with those of effluent discharged from a pulp and paper mill.

The current structure is characterized in terms of its mean and fluctuations. In profile view at mid-channel the pattern of mean flow from the surface to approximately 50 m depth is westward, and at greater depth the flow is eastward. In plan view there is a countercurrent directed eastward from surface to bottom bordering the U.S. shore. The fluctuations, as characterized by measured variance, are lowest in the Harbor and fiftyfold greater in its approaches. The variance measured in the Harbor is twentyfold higher than computed from the rise and fall of local tides.

The energetic behavior of the Harbor is primarily attributed to tidal eddies and wind effects. Tidal eddies are generated within the Harbor by "forcing" from the more energetic exterior tidal flows. These eddies are constrained in size by the Harbor dimensions, and create complex flow patterns. Outside the Harbor some tidal eddies were found to grow a hundredfold in area during a major flood or ebb. Sulfite waste liquor was used as an indicator of wind effect because it is concentrated near the water surface. The prevailing winds are from the west in most months and apparently drive the sulfite waste liquor eastward out of the Harbor.

The residence period of contaminants within the Harbor was estimated from experiments in the tidal model and from the decrease in sulfite waste liquor after abrupt decreases of input from the pulp and paper mills. The results suggest for the surface layers a residence period of several days to a week depending on release site and time. There is insufficient data to determine the residence period at depth, particularly below sill depth (44 m). The model experiments suggest that the tidal flows around the tip of Ediz Hook may induce a weak flow in the Harbor. However the net flow in the Harbor cannot be determined at present because there are no long term current meter records.

Once outside the Harbor, both the wind effects and the mean countercurrent favor eastward transport of contaminants, whereas tidal eddies laterally disperse materials both from the shore to mid-channel and from offshore to the beach. The transport and dispersion is illustrated by the behavior of a previous oil spill, suspended sediment from local rivers, creeks, and cliffs, effluent from a pulp and paper mill, dye released in the hydraulic tidal model, and drift sheets and drift cards released in and near the Harbor. Concentrations and effects of pulp mill effluent have been observed as far east as Dungeness Spit. However dye released in the hydraulic tidal model indicates that contaminants could reach behind Dungeness Spit and to the mouths of Sequim and Discovery bays. Recoveries onshore of drift sheets and cards show similar transport and dispersion from Port Angeles Harbor, with drift cards reaching a wide area including Sequim and Discovery bays, Puget Sound, Whidbey Basin and the Strait of Georgia.

It is evident that oil spilled in or near Port Angeles Harbor will be transported over a wide area, with largest impact to the shoreline occurring directly eastward of the Harbor including Dungeness Spit. Some oil will likely reach Puget Sound and the Strait of Georgia by surface transport and by downwelling and transport inland at depth by the deep net estuarine flows as previously documented for Deception Pass. The extent of oil intrusion into Puget Sound and the Strait of Georgia at depth remains to be determined.

ACKNOWLEDGEMENTS

We are indebted to John H. Lincoln for advice in the construction and operation of the hydraulic tidal model; and to Professor Emeritus Clifford A. Barnes for discussion of estuarine systems. Critical reviews by Clifford A. Barnes and Ronald Kopenski significantly improved the work.

The authors also express appreciation to Richard J. Callaway, Ronald Kopenski, Commander Jimmy A. Lyons, James Moore, Kathy Pazera, Roger Tollefson, Thomas Waite, and John Yearsley for assistance in locating important field data. We also thank David B. Browning for assistance in preparing the photographs.

Current meter records were supplied by personnel from the Environmental Protection Agency, National Oceanographic Data Center, and the National Ocean Survey. Aerial reconnaissance photographs were supplied by the U.S. Army Corps of Engineers, Seattle, and the Environmental Protection Agency, Las Vegas. U.S. Coast Guard personnel at Ediz Hook provided invaluable assistance on several occasions.

This work was supported by the Office of Energy, Minerals, and Industry, Office of Research and Development, U.S. Environmental Protection Agency through an interagency agreement with the Environmental Research Laboratories of NOAA. The work was administrated under contract no. NA79RAC00009 to Evans-Hamilton, Inc. from NOAA.

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APPENDIX A

Index to Historical Oceanographic Data

APPENDIX A.1

Index to Historical Oceanographic Data: Summary of Currents Observed For Less Than Several Days in Port Angeles Harbor and Vicinity

APPENDIX A.1. SUMMARY OF CURRENTS OBSERVED FOR LESS THAN SEVERAL DAYS IN PORT ANGELES HARBOR AND VICINITY.

Reference	Observation depth (m)	Mean* speed ($m\ s^{-1}$)	Net Current* direction (°True toward)	Number of observations	Observation		Latitude 48°N- (minutes)	Longitude 123°W- (minutes)
					period	duration (hours)		
1. Stein and Denison	0	0.081	60	13	summer 1965	0.3	7.30	24.37
(1966)	6	0.061	77	13	summer 1965	0.3	7.30	24.37
2. Wash. St. Pollution	5	Unknown	Unknown	1	14-18 July 1964	100.0	8.30	24.87
Control Commission	27	Unknown	Unknown	1	14-18 July 1964	100.0	8.30	24.87
(1967)	44	Unknown	Unknown	1	14-18 July 1964	100.0	8.30	24.87
					5-27-70			
3. Tollefson *et al.*	2	0.102	193	5	5-27-70	0.2	7.60	24.12
(1971)	8	0.077	299	4	5-27-70	0.2	7.60	24.12
	13	0.080	325	4	5-27-70	0.2	7.60	24.12
	2	0.054	294	4	5-28-70	0.2	7.28	22.85
	8	0.038	221	3	5-28-70	0.2	7.28	22.85
	13	0.020	300	3	5-28-70	0.2	7.28	22.85
	2	0.047	88	2	6-10-70	0.2	7.60	24.12
	8	0.062	106	2	6-10-70	0.2	7.60	24.12
	2	0.089	178	4	6-11-70	0.2	7.60	24.12
	4	0.061	168	3	6-11-70	0.2	7.60	24.12
	8	0.064	191	4	6-11-70	0.2	7.60	24.12
	2	0.624	28	2	7-14-70	0.2	8.45	23.45
	4	0.668	017	2	7-14-70	0.2	8.45	23.45
	20	0.119	119	2	7-14-70	0.2	8.45	23.45
	2	0.470	79	6	7-15-70	0.2	8.45	23.45
	4	0.370	160	3	7-15-70	0.2	8.45	23.45
	8	0.229	116	3	7-15-70	0.2	8.45	23.45
	30	0.186	145	3	7-15-70	0.2	8.45	23.45
	60	0.216	102	4	7-15-70	0.2	8.45	23.45
	2	0.084	48	3	7-17-70	0.2	8.45	23.45
	4	0.049	31	2	7-17-70	0.2	8.45	23.45
	20	0.280	135	2	7-17-70	0.2	8.45	23.45
	30	0.111	105	2	7-17-70	0.2	8.45	23.45
	58	0.065	175	2	7-17-70	0.2	8.45	23.45

APPENDIX A.1 (continued)

Reference	Observation depth (m)	Mean* speed (m s^{-1})	Net Current* direction (°True toward)	Number of observations	Observation period	Observation duration (hours)	Latitude 48°N- (minutes)	Longitude 123°W- (minutes)
3. Tollefson *et al.* (1971) cont.	2	0.555	264	2	7-23-70	0.2	8.45	23.45
	60	0.150	298	2	7-23-70	0.2	8.45	23.45
	2	0.255	278	4	7-24-70	0.2	7.60	24.12
	4	0.205	315	2	7-24-70	0.2	7.60	24.12
	8	0.295	290	2	7-24-70	0.2	7.60	24.12
	10	0.182	319	4	7-24-70	0.2	7.60	24.12
	2	0.996	93	3	7-28-70	0.2	8.45	23.45
	4	0.123	138	2	7-28-70	0.2	8.45	23.45
	20	0.524	86	2	7-28-70	0.2	8.45	23.45
	60	0.222	139	4	7-28-70	0.2	8.45	23.45
	2	0.140	352	7	7-30-70	0.2	7.60	24.12
	4	0.132	338	5	7-30-70	0.2	7.60	24.12
	8	0.146	295	4	7-30-70	0.2	7.60	24.12
	10	0.425	317	2	7-30-70	0.2	7.60	24.12
	10	Unknown	Unknown	1	7-30-70	2.9	7.60	24.12
	15	0.227	310	4	7-30-70	0.2	7.60	24.12
	2	0.403	204	5	7-31-70	0.2	7.60	24.12
	4	0.092	207	5	7-31-70	0.2	7.60	24.12
	8	0.086	176	3	7-31-70	0.2	7.60	24.12
	10	0.129	134	2	7-31-70	0.2	7.60	24.12
	10	Unknown	Unknown	1	7-31-70	2.3	7.60	24.12
	13	0.043	87	3	7-31-70	0.2	7.60	24.12
	2	0.494	253	3	8-6-70	0.2	8.45	23.45
	4	0.598	259	3	8-6-70	0.2	8.45	23.45
	8	0.637	279	2	8-6-70	0.2	8.45	23.45
	30	0.225	217	3	8-6-70	0.2	8.45	23.45
	57	0.648	106	3	8-6-70	0.2	8.45	23.45
	2	0.491	301	3	8-7-70	0.2	8.45	23.45
	4	0.507	286	4	8-7-70	0.2	8.45	23.45
	8	0.388	290	3	8-7-70	0.2	8.45	23.45
	10	0.511	299	3	8-7-70	0.2	8.45	23.45
	20	0.291	308	3	8-7-70	0.2	8.45	23.45
	30	0.281	295	5	8-7-70	0.2	8.45	23.45
	55	0.258	338	4	8-7-70	0.2	8.45	23.45

APPENDIX A.1 (continued)

Reference	Observation depth (m)	Mean* speed (m s^{-1})	Net Current* direction (°True toward)	Number of observations	Observation period	Observation duration (hours)	Latitude 48°N- (minutes)	Longitude 123°W- (minutes)
3. Tollefson *et al.* (1971) cont.	2	0.318	99	3	8-11-70	0.2	7.60	24.12
	4	0.285	98	2	8-11-70	0.2	7.60	24.12
	10	0.161	132	3	8-11-70	0.2	7.60	24.12
	15	0.100	276	2	8-11-70	0.2	7.60	24.12
	2	0.021	334	12	8-12-70	0.2	7.60	24.12
	4	0.080	330	12	8-12-70	0.2	7.60	24.12
	8	0.072	307	11	8-12-70	0.2	7.60	24.12
	10	0.071	318	11	8-12-70	0.2	7.60	24.12
	12	0.110	322	12	8-12-70	0.2	7.60	24.12
	15	0.120	219	11	8-12-70	0.2	7.60	24.12
	2	0.078	303	14	8-13-70	0.2	7.60	24.12
	4	0.070	307	14	8-13-70	0.2	7.60	24.12
	8	0.069	297	14	8-13-70	0.2	7.60	24.12
	10	0.080	329	16	8-13-70	0.2	7.60	24.12
	10	Unknown	Unknown	1	8-13-70	13.6	7.60	24.12
	12	0.082	312	16	8-13-70	0.2	7.60	24.12
	15	0.149	324	16	8-13-70	0.2	7.60	24.12
	2	0.465	107	8	8-14-70	0.2	8.45	23.45
	4	0.733	112	8	8-14-70	0.2	8.45	23.45
	7	0.519	70	4	8-14-70	0.2	8.45	23.45
	8	0.740	112	4	8-14-70	0.2	8.45	23.45
	10	0.544	114	8	8-14-70	0.2	8.45	23.45
	10	Unknown	Unknown	1	8-14-70	9.0	8.45	23.45
	15	0.609	111	6	8-14-70	0.2	8.45	23.45
	20	0.645	105	4	8-14-70	0.2	8.45	23.45
	40	0.396	116	4	8-14-70	0.2	8.45	23.45
	2	0.921	116	4	8-17-70	0.2	8.45	23.45
	4	0.987	111	3	8-17-70	0.2	8.45	23.45
	8	0.959	111	3	8-17-70	0.2	8.45	23.45
	10	0.528	119	2	8-17-70	0.2	8.45	23.45
	10	Unknown	Unknown	1	8-17-70	1.7	8.45	23.45
	15	0.549	711	2	8-17-70	0.2	8.45	23.45
	20	0.505	111	2	8-17-70	0.2	8.45	23.45
	40	0.665	111	2	8-17-70	0.2	8.45	23.45

APPENDIX A.1 (continued)

Reference	Observation depth (m)	Mean* speed (m s^{-1})	Net Current* direction (°True toward)	Number of observations	Observation period	duration (hours)	Latitude 48°N- (minutes)	Longitude 123°W- (minutes)
3. Tollefson et al. (1971) cont.	2	0.510	91	3	8-18-70	0.2	8.45	23.45
	4	0.163	129	4	8-18-70	0.2	8.45	23.45
	8	0.242	123	4	8-18-70	0.2	8.45	23.45
	10	0.157	140	4	8-19-70	0.2	8.45	23.45
	20	0.458	116	3	8-18-70	0.2	8.45	23.45
	40	0.914	121	2	8-18-70	0.2	8.45	23.45
	2	0.235	294	6	8-19-70	0.2	8.45	23.45
	4	0.146	289	6	8-19-70	0.2	8.45	23.45
	8	0.207	296	5	8-19-70	0.2	8.45	23.45
	10	0.078	288	5	8-19-70	0.2	8.45	23.45
	20	0.076	297	5	8-19-70	0.2	8.45	23.45
	40	0.092	102	5	8-19-70	0.2	8.45	23.45
	60	0.168	107	5	8-19-70	0.2	8.45	23.45
	2	0.332	311	6	8-20-70	0.2	8.45	23.45
	4	0.324	307	6	8-20-70	0.2	8.45	23.45
	8	0.274	315	6	8-20-70	0.2	8.45	23.45
	10	0.308	299	6	8-20-70	0.2	8.45	23.45
	10	Unknown	Unknown	1	8-20-70	0.2	8.45	23.45
	20	0.276	299	5	8-20-70	0.2	8.45	23.45
	40	0.052	278	5	8-20-70	0.2	8.45	23.45
	60	0.049	162	4	8-20-70	0.2	8.45	23.45
	2	0.050	359	2	8-28-70	0.2	7.60	24.12
	4	0.108	334	2	8-28-70	0.2	7.60	24.12
	15	0.444	341	2	8-28-70	0.2	7.60	24.12
	2	0.037	93	6	9-1-70	0.2	8.45	23.45
	4	0.019	304	6	9-1-70	0.2	8.45	23.45
	8	0.035	284	7	9-1-70	0.2	8.45	23.45
	10	0.005	159	6	9-1-70	0.2	8.45	23.45
	10	Unknown	Unknown	1	9-1-70	6.2	8.45	23.45
	20	0.176	120	6	9-1-70	0.2	8.45	23.45
	40	0.305	107	6	9-1-70	0.2	8.45	23.45
	60	0.323	94	4	9-1-70	0.2	8.45	23.45

APPENDIX A.1 (continued)

Reference	Observation depth (m)	Mean* speed (m s^{-1})	Net Current* direction (°True toward)	Number of observations	Observation period	Observation duration (hours)	Latitude 48°N- (minutes)	Longitude 123°W- (minutes)
3. Tollefson *et al.* (1971) cont.	2	0.026	73	3	9-3-70	0.2	7.28	22.85
	4	0.173	111	3	9-3-70	0.2	7.28	22.85
	8	0.173	114	3	9-3-70	0.2	7.28	22.85
	10	Unknown	Unknown	1	9-29-70	4.4	7.28	22.85
	10	Unknown	Unknown	1	9-30-70	6.8	7.28	22.85
	10	Unknown	Unknown	1	10-1-70	7.2	7.28	22.85
	10	Unknown	Unknown	1	11-3-70	3.0	7.60	22.70
	10	Unknown	Unknown	1	11-4-70	5.9	7.60	22.70
	10	Unknown	Unknown	1	11-5-70	5.9	7.60	22.70
	10	Unknown	Unknown	1	11-6-70	3.4	7.60	22.70

*Mean current speeds and directions are heavily biased due to very short sampling intervals.

APPENDIX A.2

Index to Historical Oceanographic Data:

Summary of Mean and Variances For Currents

Observed For Several Days or Longer in

Port Angeles Harbor and Vicinity

APPENDIX A.2. SUMMARY OF MEAN AND VARIANCE FOR CURRENTS OBSERVED FOR SEVERAL DAYS OR LONGER IN PORT ANGELES HARBOR AND VICINITY (SEE FIG. 3.2 FOR LOCATIONS AND CURRENT PATTERN)

General location/ relative water depth (Z/d)	Observation depth, Z (m)	Mean speed ($m\ s^{-1}$)	Current direction (°True toward)	Total variance ($m^2\ s^{-2}$)	Observation period begin date	Observation period duration (days)	Latitude 48°N- (minutes)	Longitude 123°W- (minutes)
INSHORE								
1. Port Angeles Harbor[a]								
a. Z/d = 0.51	16	0.013	109	.0071	2-19-76	19	8.14	25.00
1a. Port Angeles Mouth[b]	5	0.031	160	.046	6-7-79	32	7.50	22.30
2. Green Point[a]								
a. Z/d = 0.21	5	0.133	93	.19	10-15-75	15	8.15	17.45
3. Dungeness Spit[a]								
a. Z/d = 0.04	5	0.346	78	.27	10-19-75	15	11.23	9.50
b. Z/d = 0.19	21	0.336	73	.23	10-19-75	15	11.23	9.50
c. Z/d = 0.87	92	0.157	99	.096	10-19-75	15	11.23	9.50
OFFSHORE								
4. Tongue Point[a]								
a. Z/d = 0.09	13	0.070	258	.38	2-25-76	40	11.44	39.75
b. Z/d = 0.20	27	0.079	258	.33	2-25-76	40	11.44	39.75
c. Z/d = 0.42	57	0.036	231	.30	2-25-76	40	11.44	39.75
d. Z/d = 0.90	121	0.048	111	.18	2-25-76	40	11.44	39.75
5. Elwha River[a]								
a. Z/d = 0.15	5	0.206	325	.77	9-2-75	15	10.61	32.06
b. Z/d = 0.74	23	0.226	004	.40	9-2-75	15	10.61	32.06
6. Ediz Hook[c]								
a. Z/d = 0.06	5	0.187	328	.21	4-20-63	5	9.60	24.60
b. Z/d = 0.48	42	0.135	302	.16	4-20-63	5	9.60	24.60
c. Z/d = 0.69	61	0.182	241	.14	4-20-63	5	9.60	24.60

APPENDIX A.2 (continued)

General location/ relative water depth (Z/d)	Observation depth, Z (m)	Mean speed ($m\ s^{-1}$)	Current direction (°True toward)	Total variance ($m^2\ s^{-2}$)	Observation period begin date	Observation period duration (days)	Latitude 48°N- (minutes)	Longitude 123°W- (minutes)
<u>OFFSHORE</u>								
7. Green Point[c]								
a. Z/d = 0.06	5	0.355	224	.36	7-20-64	5	11.20	17.30
b. Z/d = 0.44	39	0.104	271	.32	7-20-64	5	11.20	17.30
c. Z/d = 0.73	64	0.111	63	.27	7-20-64	5	11.20	17.30
8. Dungeness Spit[c]								
a. Z/d = 0.03	5	0.195	260	.08	8-10-64	5	13.60	8.00
b. Z/d = 0.47	69	0.140	335	.09	8-10-64	5	13.60	8.00
c. Z/d = 0.78	114	0.220	63	.27	8-10-64	5	13.60	8.00
<u>MID-CHANNEL</u>								
9. Tongue Point[a]								
a. Z/d = 0.09	16	0.270	289	.45	2-25-76	40	14.60	39.10
b. Z/d = 0.35	61	0.154	295	.38	2-25-76	40	14.60	39.10
c. Z/d = 0.71	125	0.166	96	.33	2-25-76	40	14.60	39.10
d. Z/d = 0.92	162	0.136	87	.17	2-25-76	40	14.60	39.10
10. Elwha River[a]								
a. Z/d = 0.03	5	0.403	253	.40	9-23-75	10	13.85	33.43
b. Z/d = 0.13	21	0.291	247	.43		41	13.85	33.43
c. Z/d = 0.37	61	0.088	190	.48	9- 2-75	41	13.85	33.43
d. Z/d = 0.64	107	0.135	73	.39	9-23-75	41	13.85	33.43
e. Z/d = 0.91	151	0.119	68	.27	10-8-75	41	13.85	33-43
11. Green Point[a]								
a. Z/d = 0.04	5	0.137	271	.35	9- 2-75	15	16.70	22.00
b. Z/d = 0.17	21	0.067	279	.37	9- 2-75	15	16.70	22.00
c. Z/d = 0.49	61	0.179	84	.43	9- 2-75	15	16.70	22.00
d. Z/d = 0.88	109	0.181	60	.28	9- 2-75	15	16.70	22.00

APPENDIX A.2 (continued)

General location/ relative water depth (Z/d)	Observation depth, Z (m)	Mean speed ($m\ s^{-1}$)	Current direction (°True toward)	Total variance ($m^2\ s^{-2}$)	Observation period begin date	duration (days)	Latitude 48°N- (minutes)	Longitude 123°W- (minutes)
MID-CHANNEL								
12. Dungeness Spit[a]								
a. Z/d = 0.03	5	0.120	180	.27	10-19-75	15	14.90	12.10
b. Z/d = 0.15	21	0.073	197	.23	10-19-75	15	14.90	12.10

a. Aanderaa-type current meter; unpublished data of National Ocean Survey (see Parker, 1977).

b. Aanderaa-type current meter; unpublished data of Environmental Protection Agency.

c. Currents manually recorded hourly; unpublished data of National Ocean Survey.

APPENDIX A.3

Index to Historical Oceanographic Data:

Observations of Drifting Objects

in Port Angeles Harbor

and Vicinity

APPENDIX A.3. OBSERVATIONS OF DRIFTING OBJECTS IN PORT ANGELES HARBOR AND VICINITY.

Reference	Type of Observation: Objects observed	Type of Observation: Depth (m)	Number of objects observed	Observation Period: date	Observation Period: duration (hours)	Observation Period: Average sampling interval (minutes)	Remarks
1. Peterson & Gibbs (1957)	Floats	1.2, 3.1	2	7-3-57	4.7	96	
	Floats	1.2, 3.1	2	7-24-57	3.5	30	
	Floats	1.2, 3.1	2	7-31-57	2.3	45	
	Floats	1.2, 3.1	2	8-6-57	3.6	60	
	Floats	1.2, 3.1	2	8-7-57	3.5	16	
2. Charnell (1958)	Floats	unknown	53	Oct. 1956-June 1958	unknown	unknown	53 floats were followed during 26 studies from Oct. 1956-June 1958. Raw data not available.
	Plastic envelopes	0.0	unknown	unknown	See remarks	unknown	25-50 envelopes launched each hour for one day, followed during day of launch, and collected off beaches for the following four days. Experiment done twice. Raw data not available.
3. Wash. St. Pollution Control Commission (1967)	Drogues	Unknown	8-10	Sept. 1962	Unknown	Unknown	No trajectories given. Raw data not available.
	Drogues	Unknown	8-10	Oct. 1962	Unknown	Unknown	
	Drogues	Unknown	8-10	Nov. 1962	Unknown	Unknown	
	Drogues	Unknown	8-10	Sept. 1963	Unknown	Unknown	

APPENDIX A.3 (continued)

Reference	Type of Observation: Objects observed	Depth (m)	Number of objects observed	Observation Period: date	duration	Average sampling interval (minutes)	Remarks
4. Tollefson *et al.* (1971)	Drogues	1.0,1.8,3.6,6.7	4	5-27-70	9.6	109	
	Drogues	1.2,4.0,7.0	3	5-28-70	6.5	117	
	Drogues	2.0,4.0,8.0	3	6-12-70	5.3	53	
	Drogues	0.0,2.0,4.0,8.0	4	7-9-70	6.0	93	
	Drogues	0.0,2.0,4.0,8.0	4	7-10-70	5.5	86	
	Drogues	0.0,2.0,4.0,8.0	8	7-15-70	8.3	79	
	Drogues	0.0,2.0,4.0,8.0	7	7-17-70	3.2	86	
	Drogues	4.0	8	7-21-70	3.3	61	
	Drogues	4.0	8	7-22-70	6.8	84	
	Drogues	4.0	15	7-23-70	4.6	89	
	Drogues	4.0	15	7-24-70	5.5	70	
	Drogues	4.0	6	7-27-70	1.0	57	
	Drogues	4.0	11	7-28-70	6.6	73	
	Drogues	4.0	6	7-29-70	4.9	68	
	Drogues	4.0	12	7-30-70	6.4	98	
	Drogues	4.0	13	7-31-70	3.7	61	
	Drogues	4.0	13	8-6-70	6.7	71	
	Drogues	4.0	10	8-7-70	4.3	61	
	Drogues	4.0	7	8-12-70	3.8	75	
	Drogues	4.0	10	8-13-70	13.6	72	
	Drogues	4.0	6	8-14-70	9.4	102	
	Drogues	4.0	6	8-17-70	2.6	45	
	Drogues	4.0	6	8-18-70	6.4	48	
	Drogues	4.0	9	8-19-70	7.4	59	
	Drogues	4.0	9	8-20-70	7.9	61	
	Drogues	4.0	8	8-25-70	7.4	61	
	Drogues	4.0	7	8-28-70	6.7	92	
	Drogues	4.0	7	8-31-70	1.3	60	
	Drogues	4.0	8	9-1-70	7.1	73	
	Drogues	4.0	15	9-2-70	7.4	90	
	Drogues	4.0	8	9-3-70	6.2	77	
	Drogues	4.0	7	12-4-70	4.0	29	
	Drogues	4.0	8	12-9-70	5.3	38	
	Drogues	4.0	8	12-10-70	6.5	49	

APPENDIX A.3 (continued)

Reference	Type of Observation: Objects observed	Depth	Number of objects observed	date	Observation Period: duration (hours)	Average sampling interval (minutes)	Remarks
5. Environmental Protection Agency (1974)	Drogue	0.0,3.0,6.0,12.0	4	4-24-73	1.2	8	Drogues were launched over ITT outfall three times.
	Drogue	0.0,3.0,6.0,12.0	4	4-24-73	0.9	8	
	Drogue	0.0,3.0,6.0,12.0	4	4-24-73	1.2	9	
	Drogue	1.6,4.6,6.1,12.2	4	7-25-73	1.0	unknown	Drogues launched over ITT outfall twice.
	Drogue	1.6,4.6,6.1,12.2	4	7-25-73	1.0	unknown	
6. Ebbesmeyer <u>et al</u>. (1978)	Drift sheets	0.0	9	4-23-78	3.0	48	
	Drogues	1.0	6	4-23-78	7.7	45	
	Drift sheets	0.0	23	4-24-78	12.4	72	
	Drogues	1.0	4	4-24-78	2.5	42	
	Drift cards	0.0	100	4-24-78	varies	None	32 later recovered onshore.
	Drift sheets	0.0	29	4-25-78	11.9	67	
	Drogues	1.0	8	4-25-78	7.2	23	
	Drift cards	0.0	100	4-25-78	varies	None	21 later recovered onshore.
	Drift sheets	0.0	17	4-26-78	8.6	31	
	Drogues	1.0	7	4-26-78	8.7	24	
	Drift cards	0.0	100	4-26-78	varies	None	31 later recovered onshore.
	Drift sheets	0.0	13	4-27-78	12.3	34	
	Drogues	1.0	4	4-27-78	9.8	21	
	Drift cards	0.0	100	4-27-78	varies	None	71 later recovered onshore.
	Drift sheets	0.0	15	4-28-78	11.9	21	
	Drogues	1.0	11	4-28-78	11.5	22	
	Drift sheets	0.0	18	4-29-78	12.9	45	
	Drogues	1.0,9.0	9	4-29-78	12.0	36	
	Drift cards	0.0	300	4-30-78	varies	None	85 later recovered onshore.
7. Cox <u>et al</u>. (1978)	Drift sheets	0.0	10	8-22-78	10.8	51	
	Drift sheets	0.0	11	8-23-78	10.7	61	
	Drift sheets	0.0	28	8-24-78	10.6	59	
	Drift sheets	0.0	39	8-25-78	13.7	89	
	Drift sheets	0.0	50	8-26-78	9.7	115	

APPENDIX A.3 (continued)

Reference	Type of Observation: Objects observed	Type of Observation: Depth	Number of objects observed	date	Observation Period: duration (hours)	Observation Period: Average sampling interval (minutes)	Remarks
8. Pashinski and Charnell (1979)	Drift cards	0.0	500	4-5-76	varies	None	178 later recovered onshore.
	Drift cards	0.0	500	4-14-76	varies	None	278 later recovered onshore.
	Drift cards	0.0	400	7-22-76	varies	None	202 later recovered onshore.
	Drift cards	0.0	1800	2-15-77	varies	None	217 later recovered onshore.
	Drift cards	0.0	800	5-17-77	varies	None	410 later recovered onshore.
	Drift cards	0.0	1000	7-20-77	varies	None	185 later recovered onshore.

APPENDIX A.4

Index to Historical Oceanographic Data:

Observations of Water Properties

in Port Angeles Harbor

and Vicinity

APPENDIX A.4 OBSERVATIONS OF WATER PROPERTIES IN PORT ANGELES HARBOR AND VICINITY.

	Reference	Parameters observed	Number of surveys	Number of stations per survey	Observation period	Remarks
1.	Westley (1956a)	Temp., Sal., D.O., S.W.L.	1	31	11 Sept. 1956	Referenced in Collias (1970) but data not included.
2.	Westley (1956b)	Temp., Sal., D.O., S.W.L., B.O.D.	1	40	16 Oct. 1956	Referenced in Collias (1970) but data not included.
3.	Peterson and Gibbs (1957)	Temp., Sal., D.O., S.W.L.	7	23	26 June-24 Sept. 1957	Physical and chemical data taken in conjunction with bacterial surveys.
4.	Charnell (1958)	Temp., Sal., D.O., S.W.L., pH	21	23	24 Aug. 1956 19 Mar. 1958	
5.	Ott et al. (1961)	Temp., Sal., D.O., S.W.L., sulfites, volatile solids	1	30	28 Nov.-7 Dec. 1961	
6.	Stein et al. (1962, 1963)	Sal., D.O., S.W.L., pH, water transparency	4	53	Unknown	Data later included in Stein and Denison (1966).
7.	Callaway et al. (1965)	Temp., Sal., D.O., S.W.L., pH, water transparency	14	18	Sept. 1962-Jan. 1964	Also described by Bartsch et al. (1967) and Wash. St. Pollution Control Commission (1967).

APPENDIX A.4 (continued)

	Reference		Parameters observed	Number of surveys	Number of stations per survey	Observation period	Remarks
8.	Stein and Denison (1966)		Sal., D.O., S.W.L., pH, water transparency	Unknown	53	1961-1966	Data from Stein *et al.* (1962, 1963) included.
9.	Wash. St. Pollution Control Commission (1967)	a.	Temp., Sal., D.O., S.W.L., pH, water transparency	9	10	July 1963-June 1964	Physical and chemical data taken in conjunction with plankton ecology surveys.
		b.	Temp., Sal., D.O., S.W.L., pH, total sulfides	13	6	April-May 1964	Physical and chemical data taken in conjunction with juvenile salmon bioassays.
		c.	Sal., S.W.L.	19	12	May 1963-August 1964; Nov. 1964	Physical and chemical data taken in conjunction with oyster larvae bioassays. Also described by Paulik (1966).
10.	U.S. Dept. of Interior (1970)		Temp., Sal., D.O., S.W.L., pH	1	26	23 July 1970	Bacteria survey also conducted.
11.	Collias (1970)		Temp., Sal., D.O., S.W.L., nutrients	several	varies	1932-1966	Index to physical and chemical hydrographic data taken by the University of Washington, Wash. St. Dept. of Fisheries, and the Pacific Oceanographic Group, Canada.

APPENDIX A.4 (continued)

	Reference	Parameters observed	Number of surveys	Number of stations per survey	Observation period	Remarks
12.	Aspitarte (1972)	Temp., Turbidity, Zinc., Sodium	1	3	18-19 Jan. 1972	Stations repeated ten times each.
13.	Aspitarte and Smale (1972)	Temp., D.O., pH, volatile solids	3	varies	13 Oct. 1971-21 Jan. 1972	Hydrographic data taken in conjunction with a study of Crown Zellerbach's sludge beds.
14.	Pine (1972)	Temp., D.O., S.W.L., pH, Turbidity, total solids, zinc.	1	6	23 Feb. 1972	
15.	Environmental (1972a) Protection Agency	Temp., Sal., D.O., S.W.L., pH, Turbidity,	1	30	3-4 May 1972	Bacteria survey also conducted.
16.	Environmental (1972b) Protection Agency	Temp., Sal., D.O., S.W.L., pH, Turbidity	1	30	31 Oct.-1 Nov. 1972	Bacteria survey also conducted.
17.	Environmental (1974) Protection Agency	Temp., Sal., D.O., pH, S.W.L., total suspended solids	1	12	23 April 1973	
18.	Moore (1976)	Temp., Sal., D.O., S.W.L., pH, dissolved total sulfides, turbidity	1	6	22-27 May 1976	Live box bioassay also conducted.
19.	Young and Cormack (1976)	Temp., D.O., pH, zinc	1	10	15 June 1976	

APPENDIX A.4 (continued)

	Reference	Parameters observed	Number of surveys	Number of stations per survey	Observation period	Remarks
20.	Fagergren (1976)	Sal., D.O., S.W.L., pH, turbidity	2	varies	17-18 June and 17-18 Aug. 1979	Stations were repeated usually seven times per survey.
21.	Denison and Fagergren (1977)	Temp., D.O., S.W.L., pH	unknown	unknown	unknown	
22.	Fagergren and Rodgers (1977)	Temp., D.O., S.W.L., pH	1	22	18-20 May 1977	
23.	Environmental Protection Agency (1979)	Temp., Sal., S.W.L., pH, B.O.D., nutrients, fluorescence	2	varies	5-9 June 1979	unpublished, oyster larvae bioassay also conducted
24.	Environmental Protection Agency (STORET)	Temp., Sal., D.O., S.W.L., nutrients				STORET is the EPA's Water Quality Data Storage and Retrieval System. Data is unpublished.
	a. University of Washington		unknown	62	1962-1964	
	b. Wash. St. Dept. of Fisheries		unknown	20	1970-1972	
	c. Wash. St. Dept. of Ecology		unknown	5	1968-1979	

APPENDIX A.5

Index to Historical Oceanographic Data:

Aerial Photographs of Port Angeles Harbor

and Vicinity

APPENDIX A.5. AERIAL PHOTOGRAPHS OF PORT ANGELES HARBOR AND VICINITY.

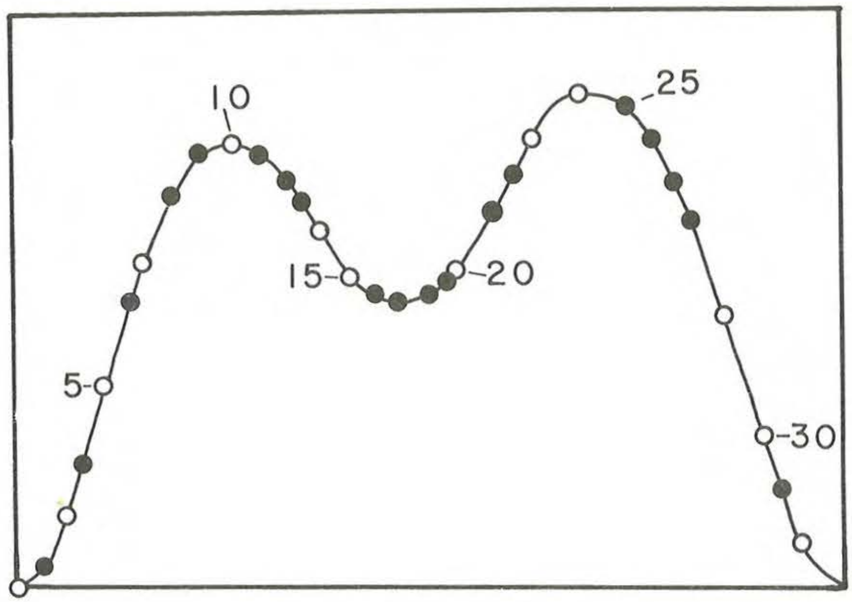
Source	Type of photograph	Observation period
1. Army Corps of Engineers	black and white	yearly surveillence flights 1970, 1972, 1974.
2. Environmental Protection Agency	a. multispectral	April-July 1973
	b. multispectral	March-April 1979.
3. ITT Rayonier, Inc.	color	June-August 1976
4. Evans-Hamilton, Inc.	a. color	April 1978
	b. color	August 1978
	c. color	June 1979

APPENDIX B

Tidal Phases of the Surface Tidal

Current Patterns in the

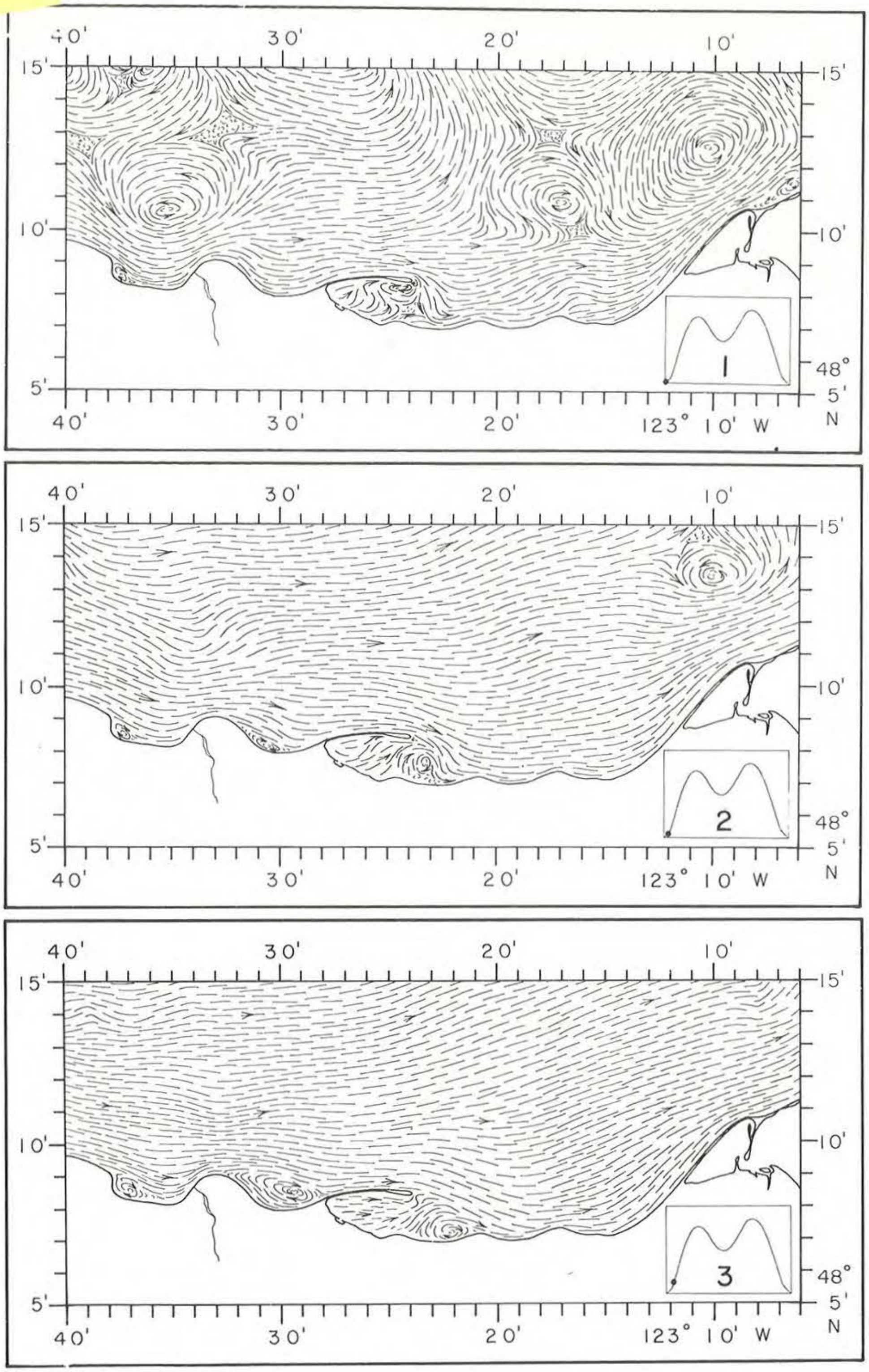
Hydraulic Tidal Model



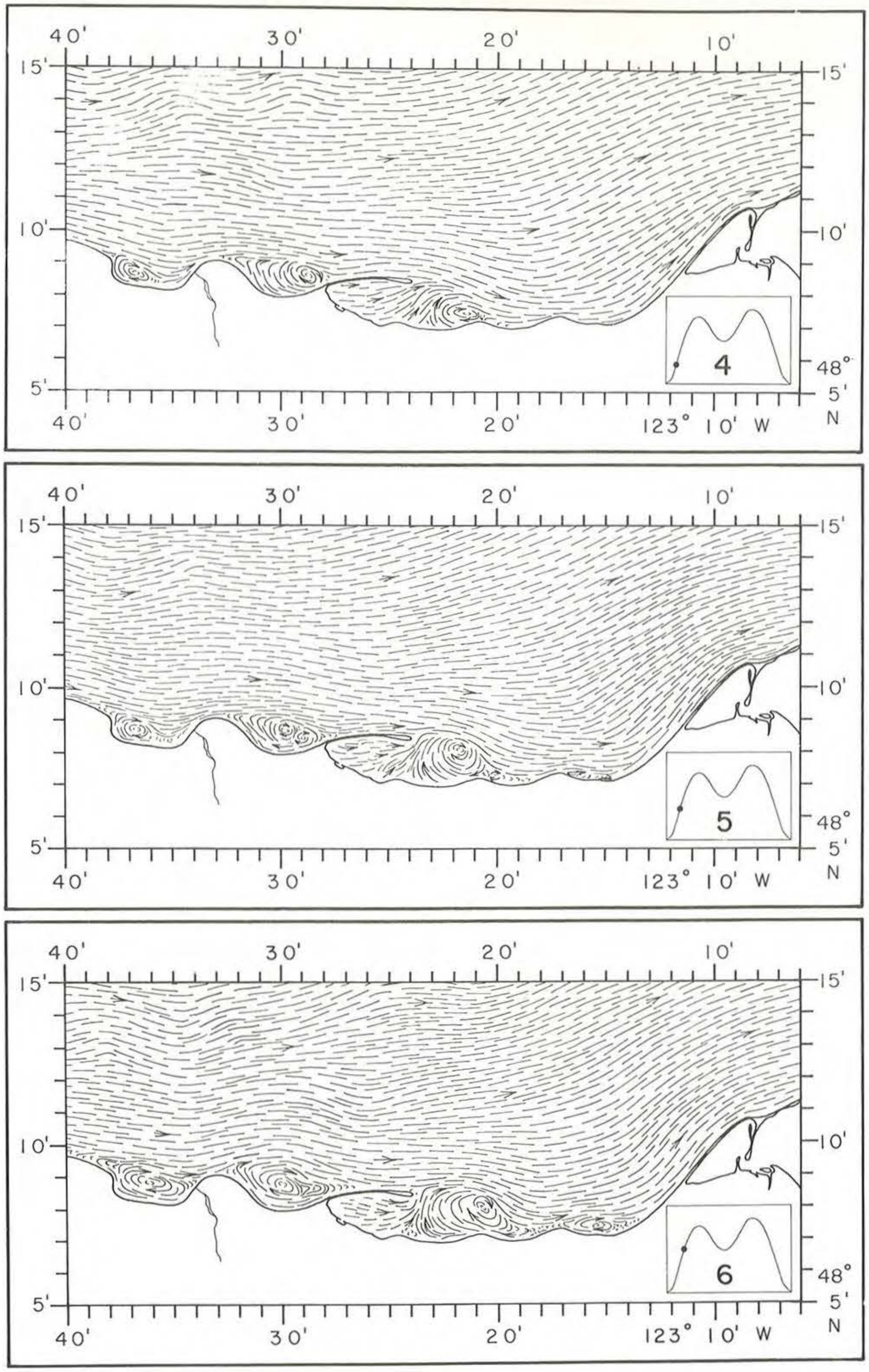
Appendix B.1. Tidal phases (dots and circles) of the surface tidal current patterns in the hydraulic tidal model. Numbers correspond to tidal current patterns in Appendix C and D. Circles indicate comparisons with field observations presented in Appendix D.

APPENDIX C

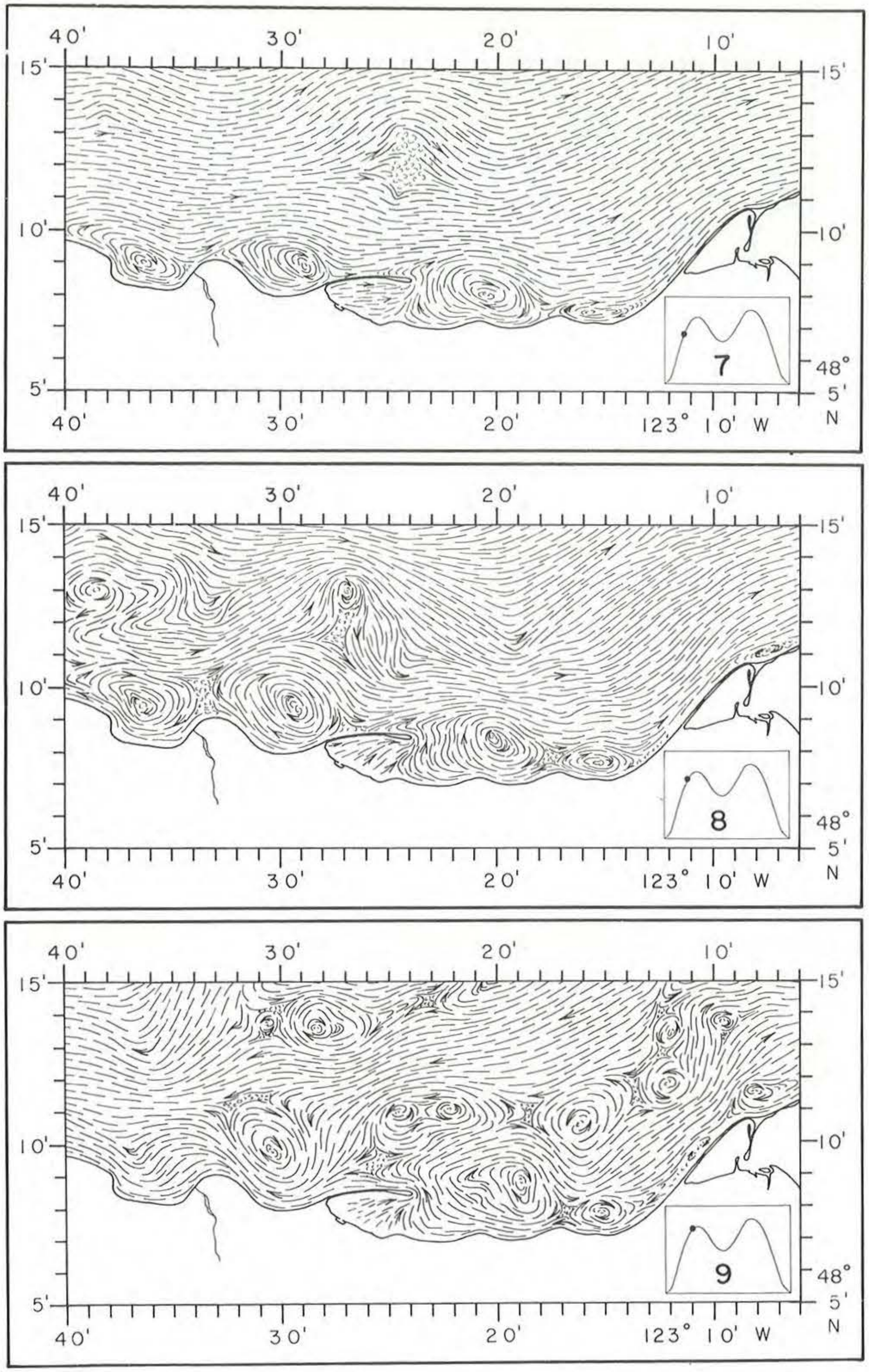
Tidal Current Patterns at Surface in the Hydraulic Tidal Model



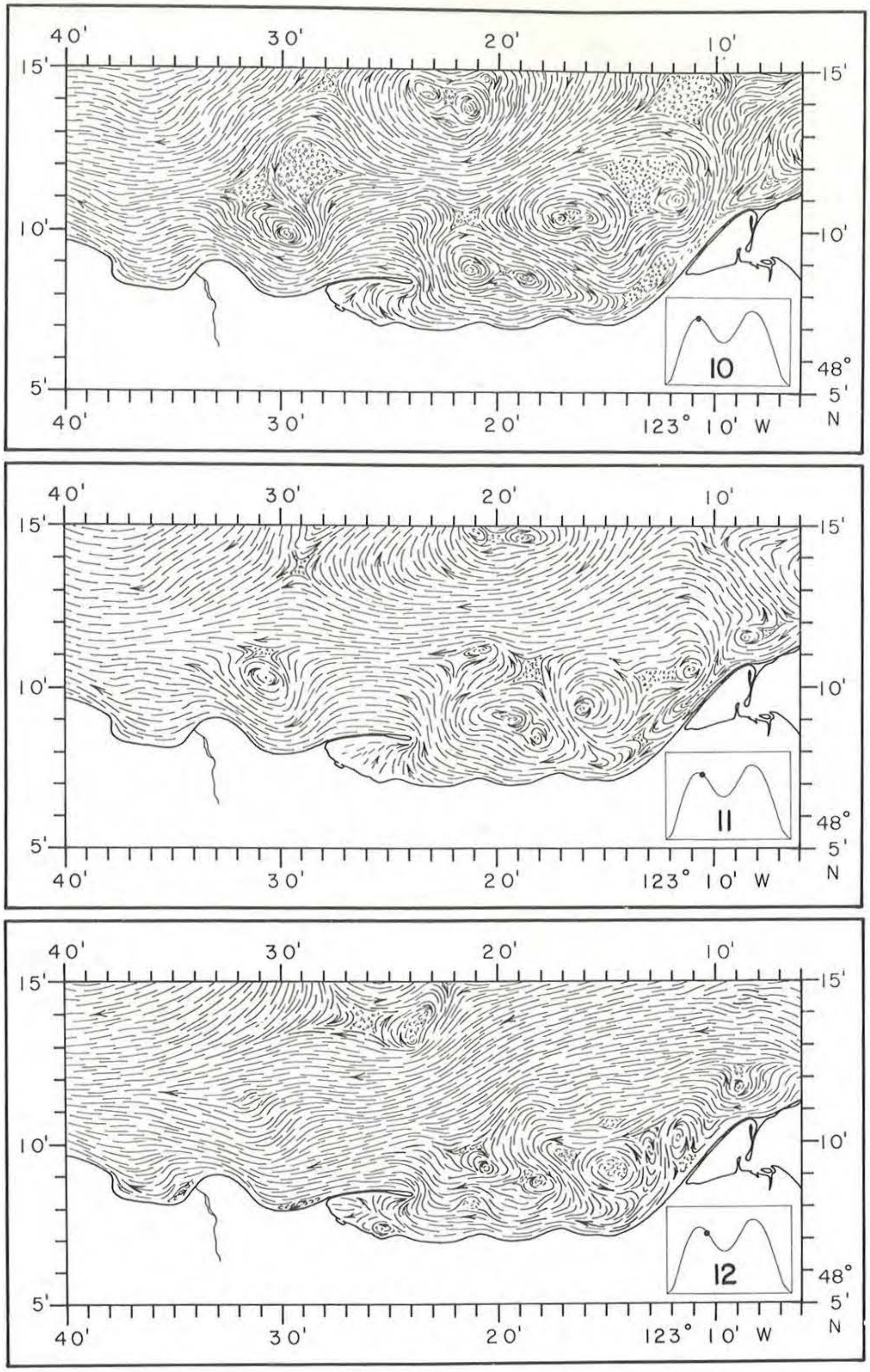
Appendix C.1-C.3. Surface tidal current patterns.



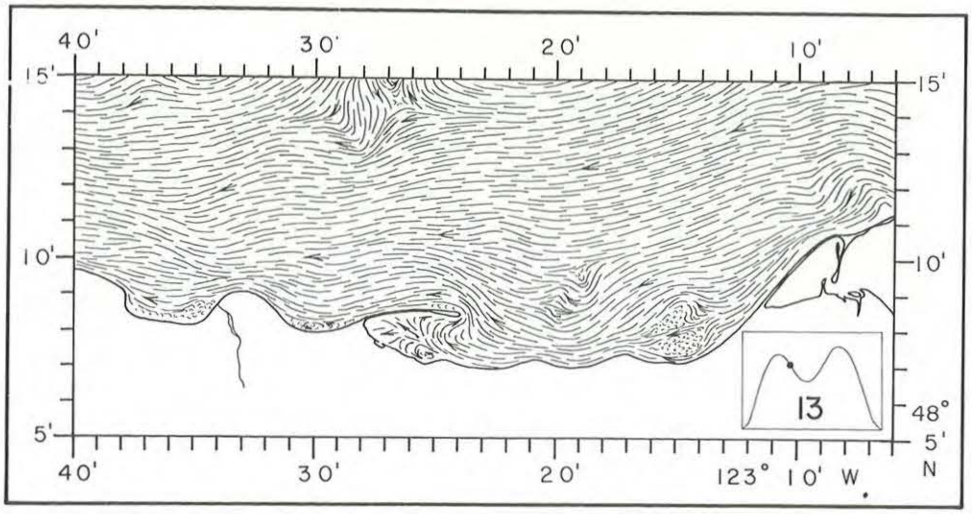
Appendix C.4-C.6. Surface tidal current patterns.

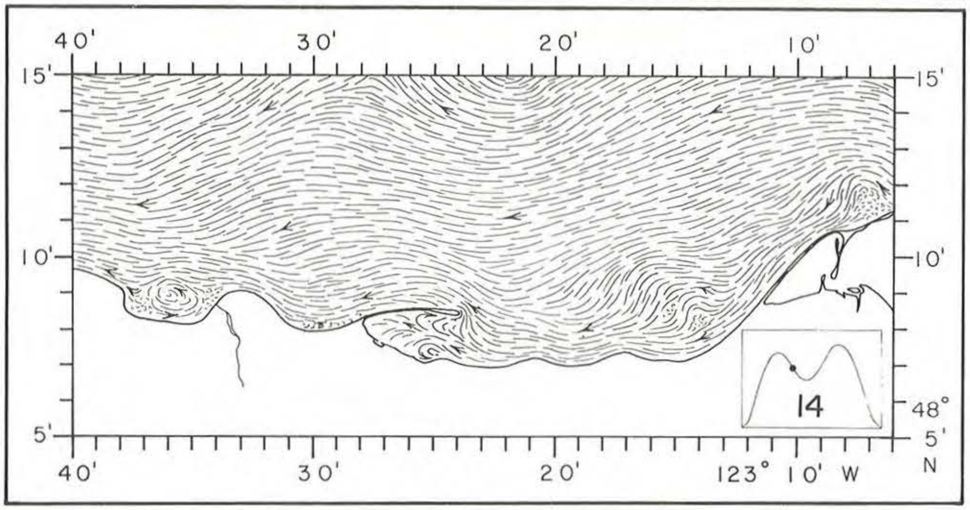


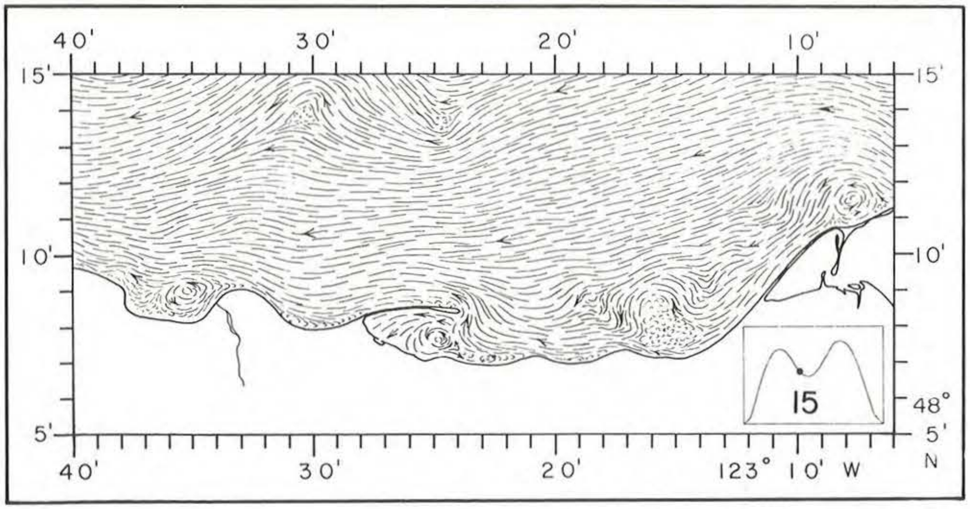
Appendix C.7-C.9. Surface tidal current patterns.



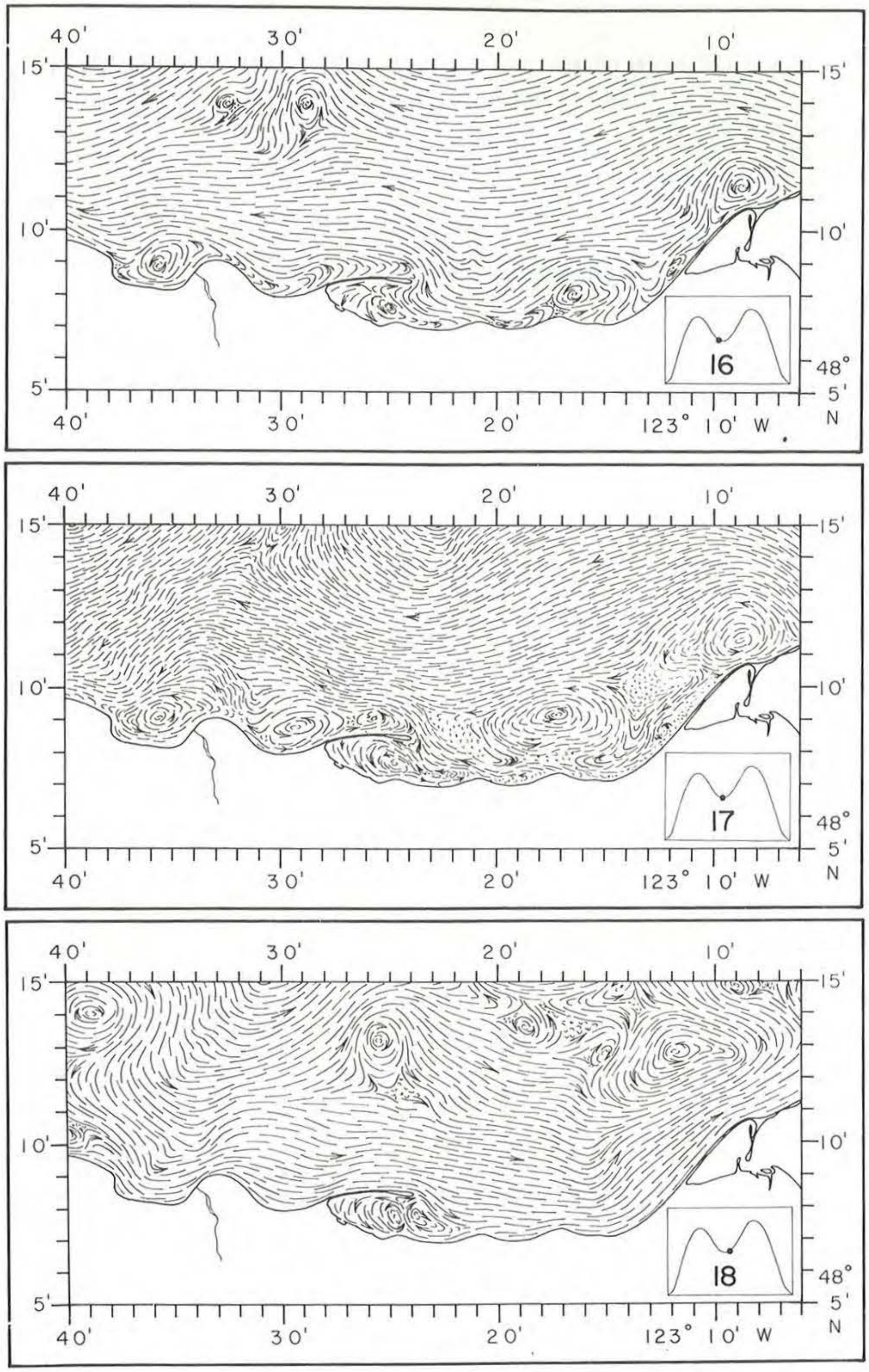
Appendix C.10-C.12. Surface tidal current patterns.



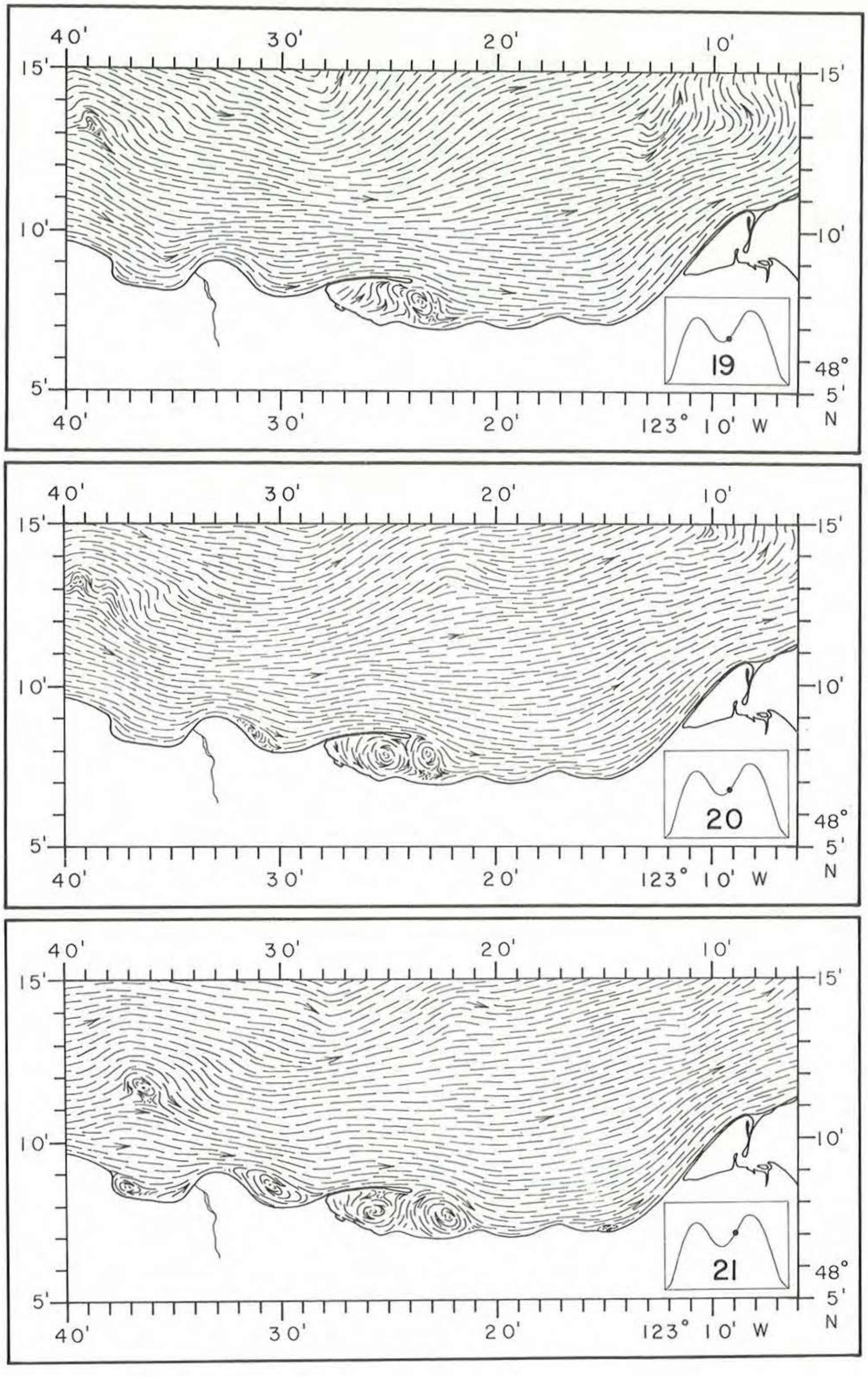




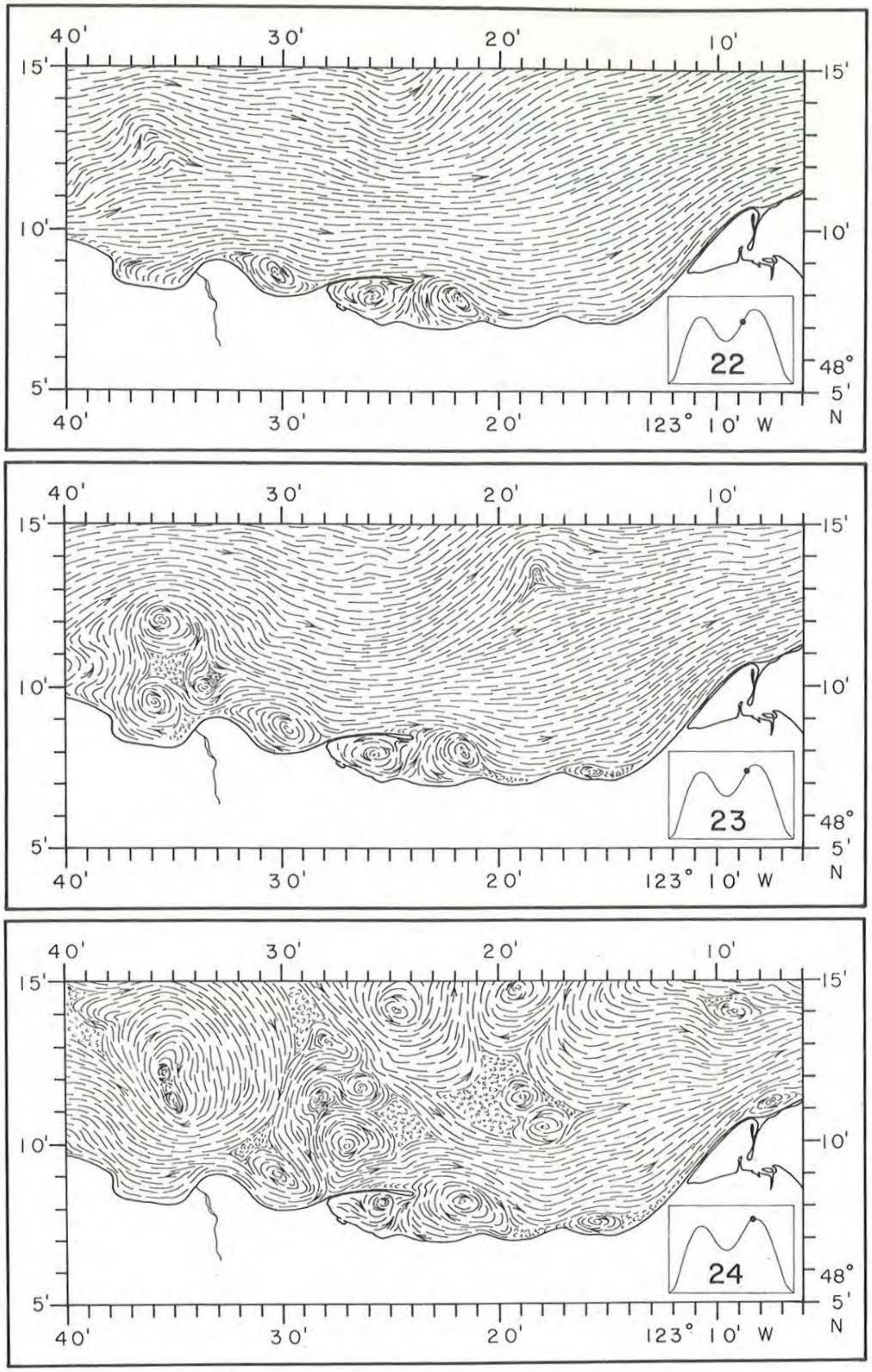
Appendix C.13-C.15. Surface tidal current patterns.



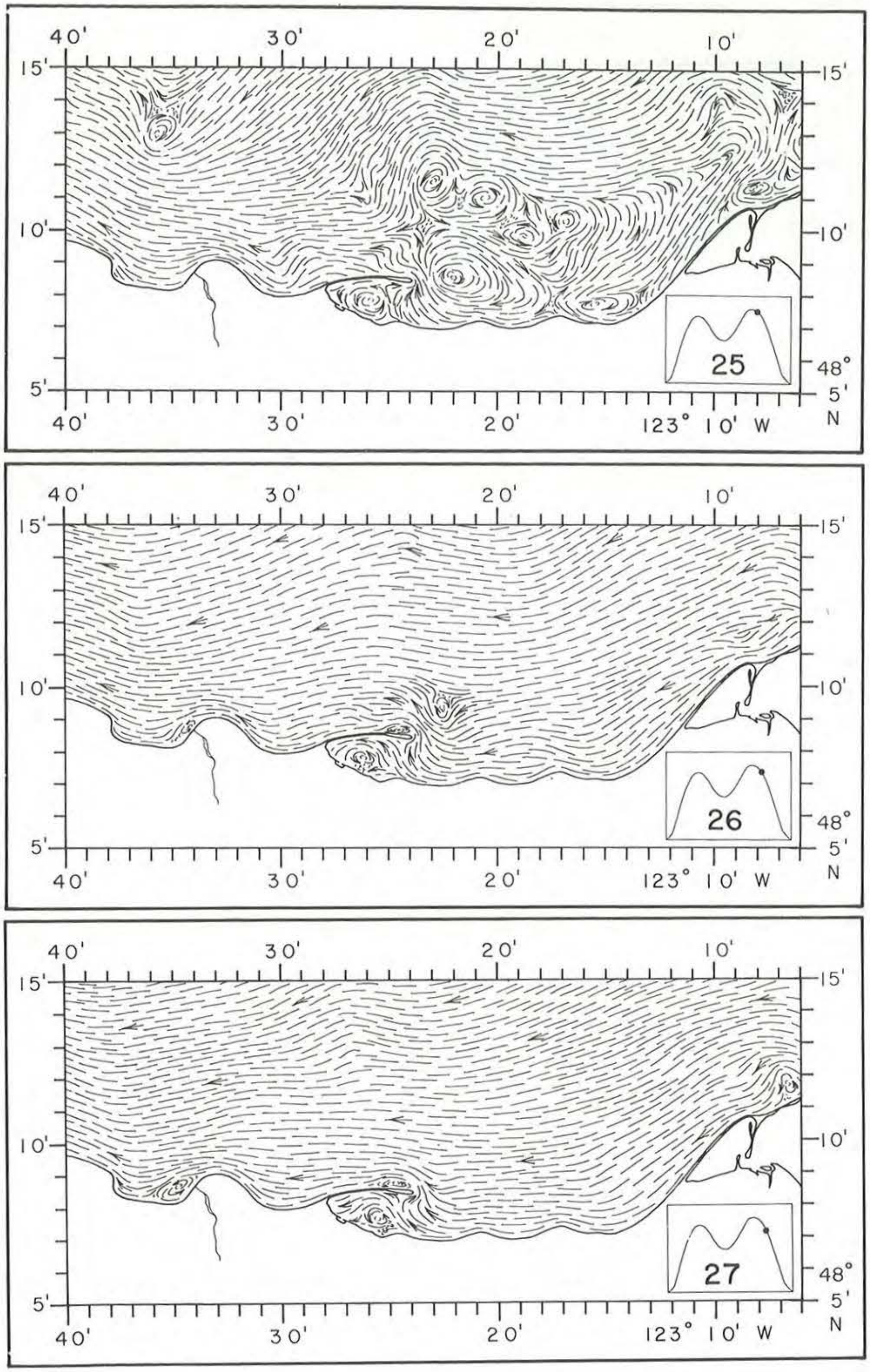
Appendix C.16-C.18. Surface tidal current patterns.



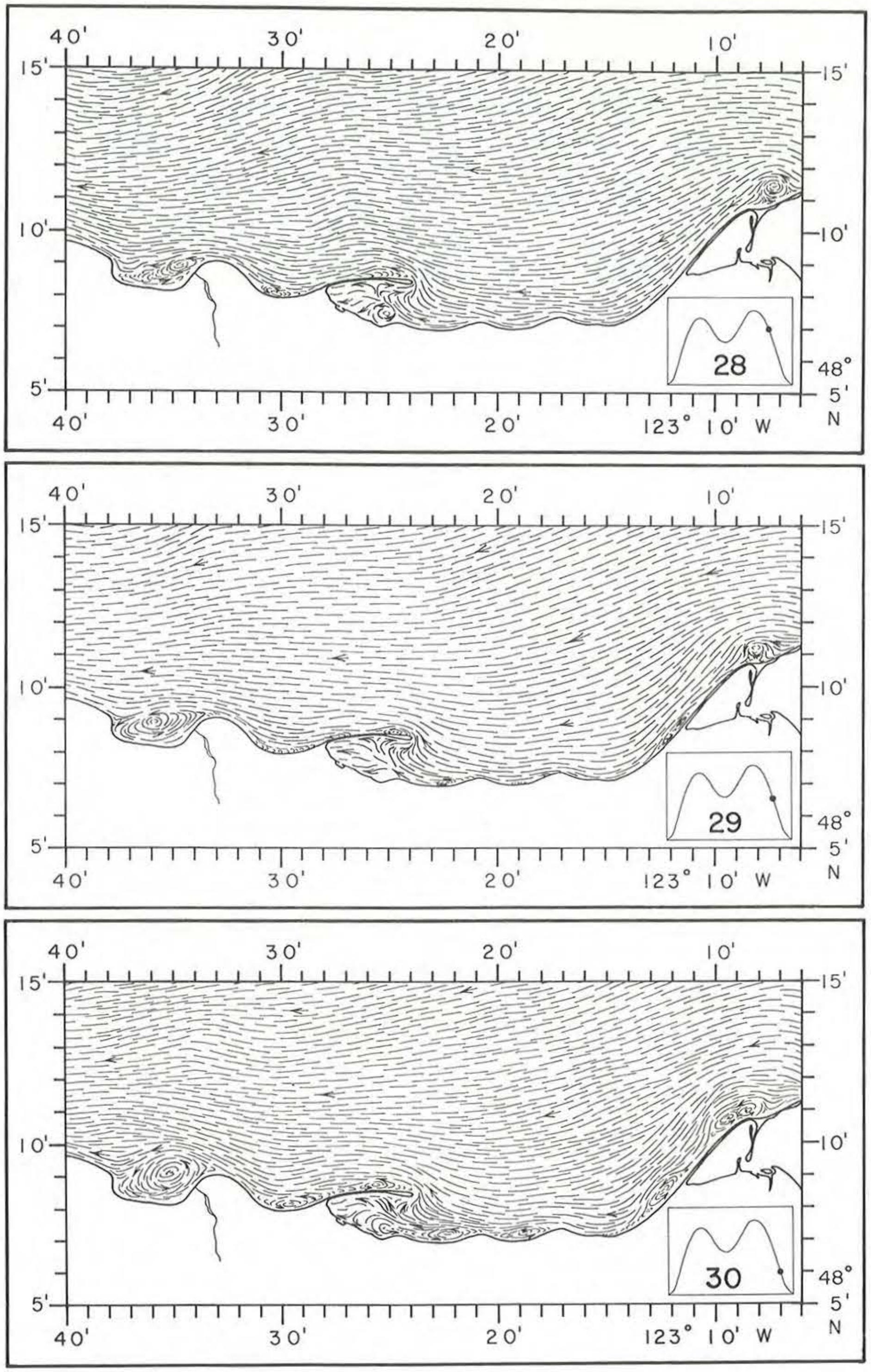
Appendix C.19-C.21. Surface tidal current patterns.



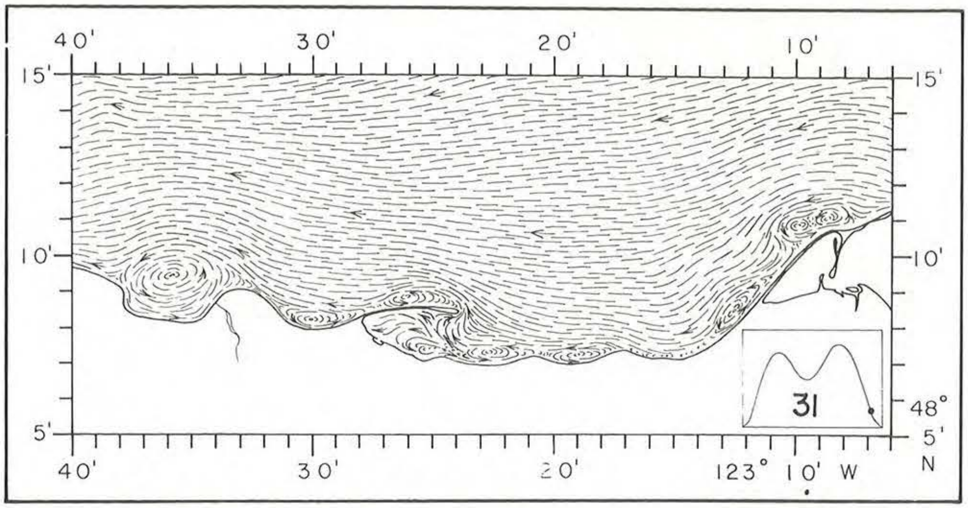
Appendix C.22-C.24. Surface tidal current patterns.

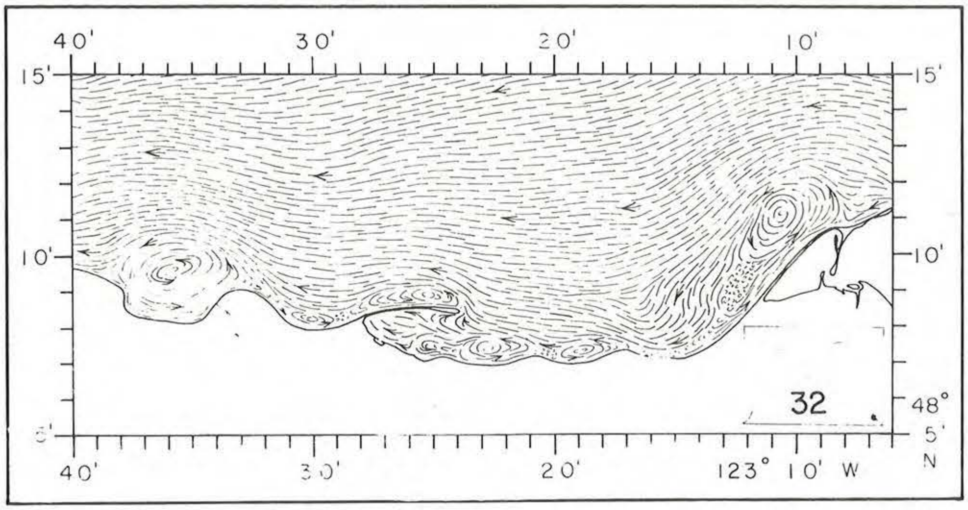


Appendix C.25-C.27. Surface tidal current patterns.



Appendix C.28-C.30. Surface tidal current patterns.





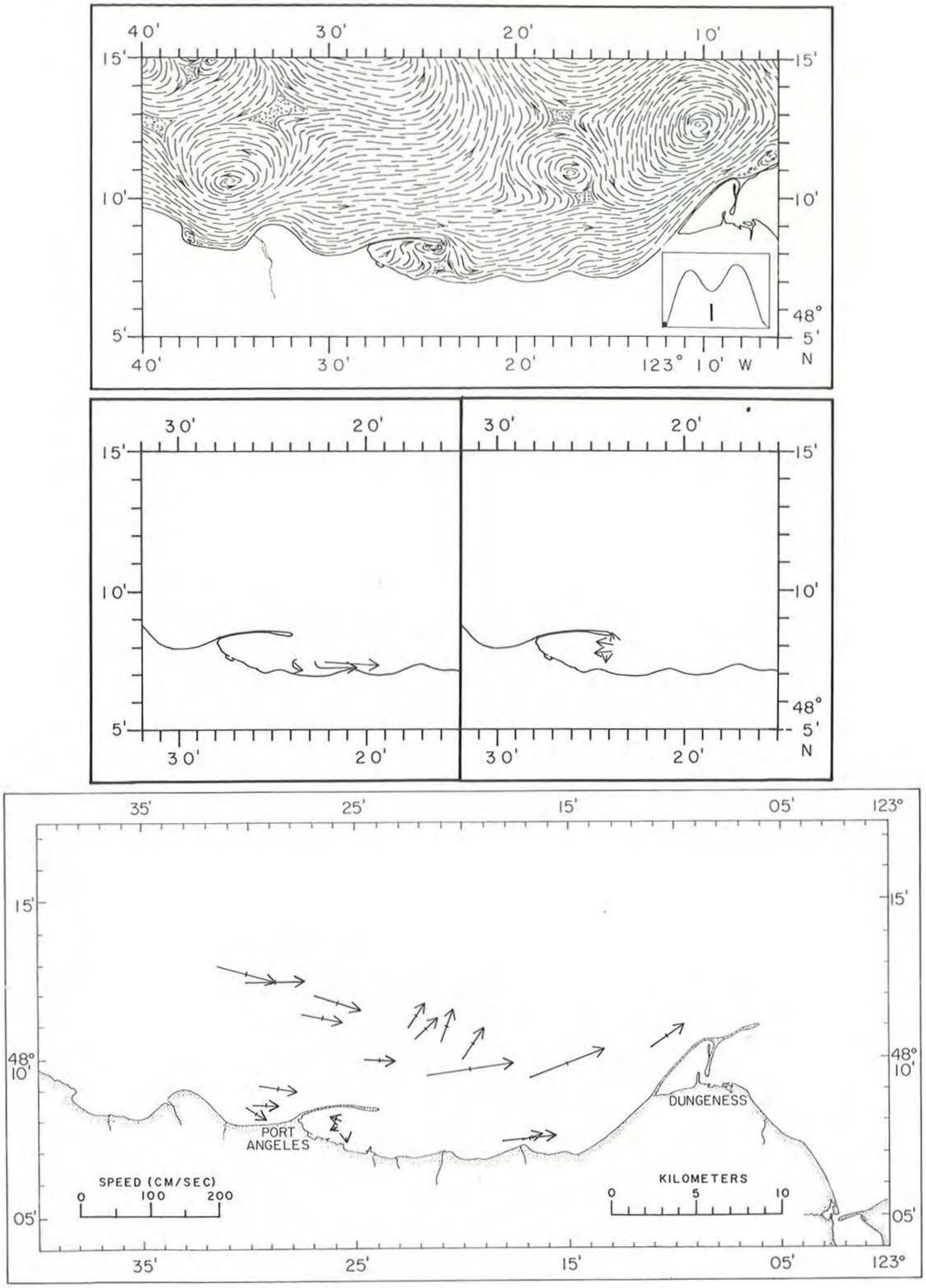
Appendix C.31-C.32. Surface tidal current patterns.

APPENDIX D

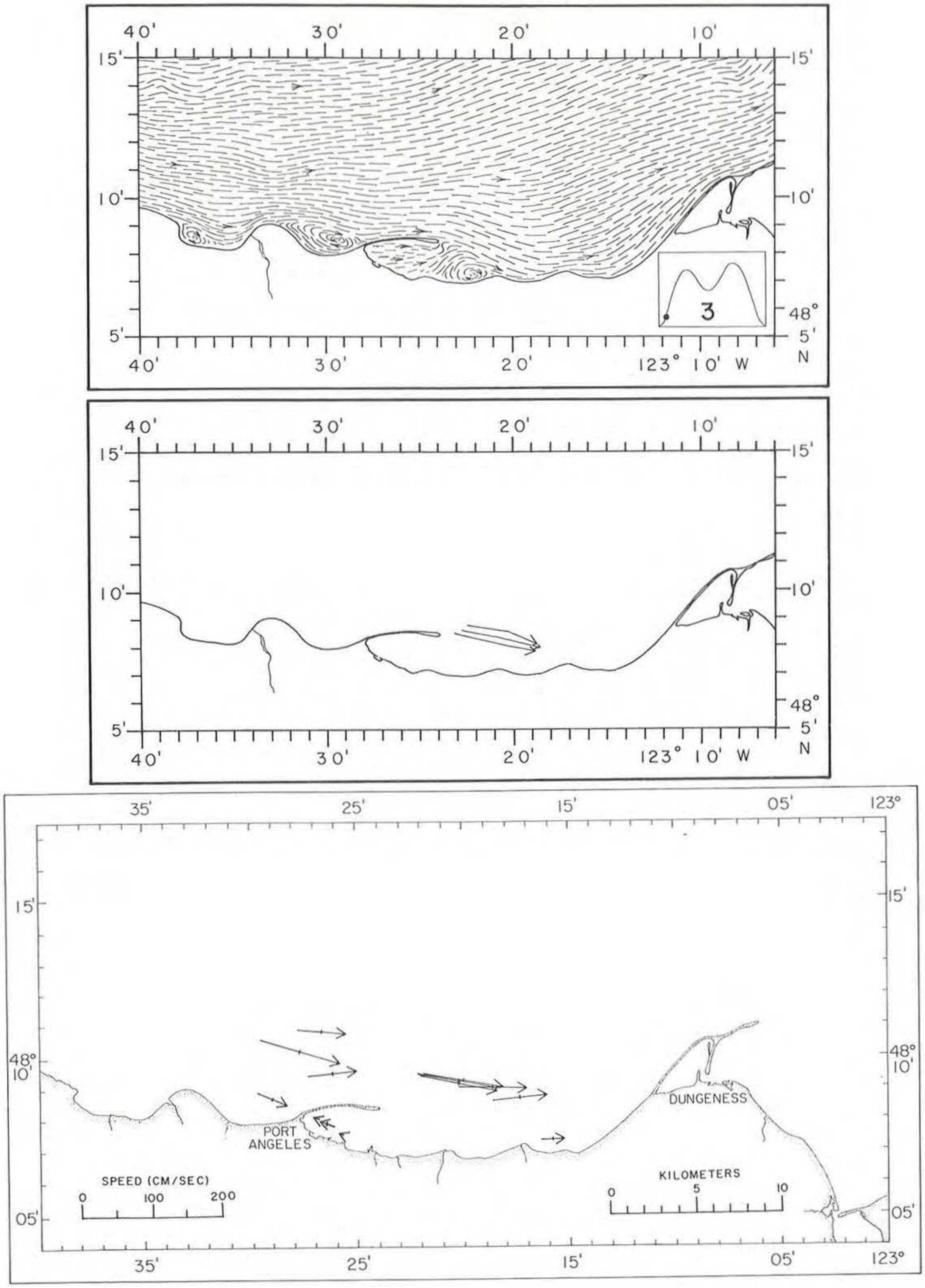
Comparison of Surface Tidal Current

Patterns in the Hydraulic Tidal Model

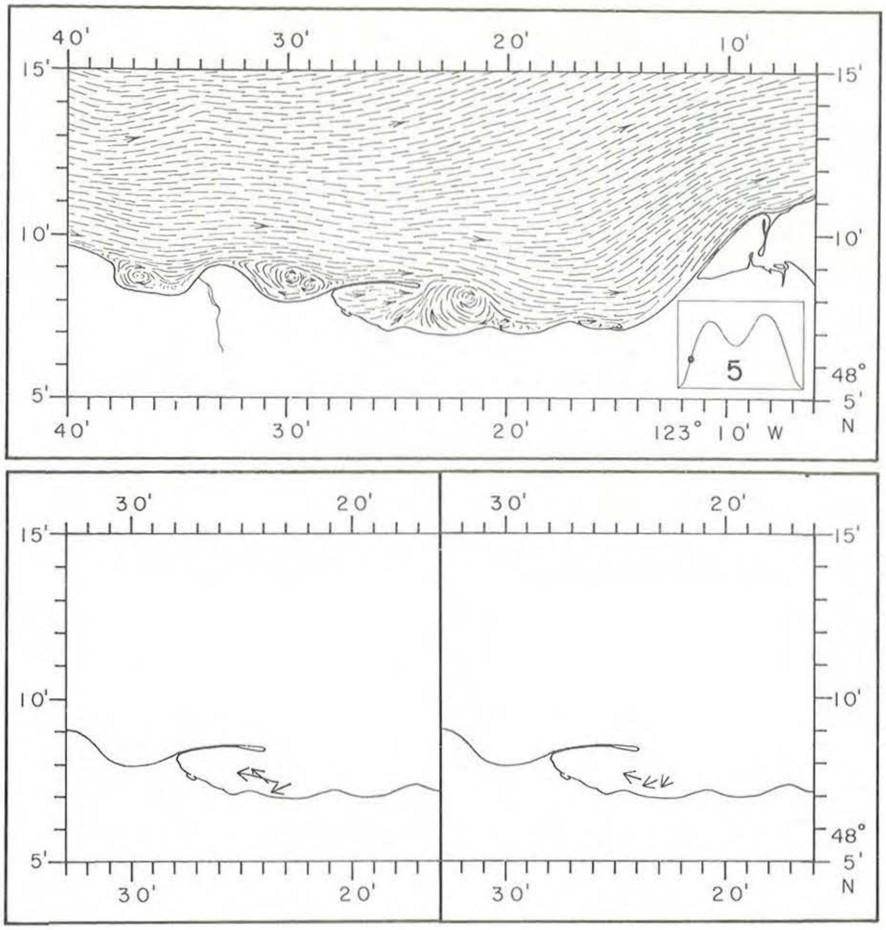
with Field Observations



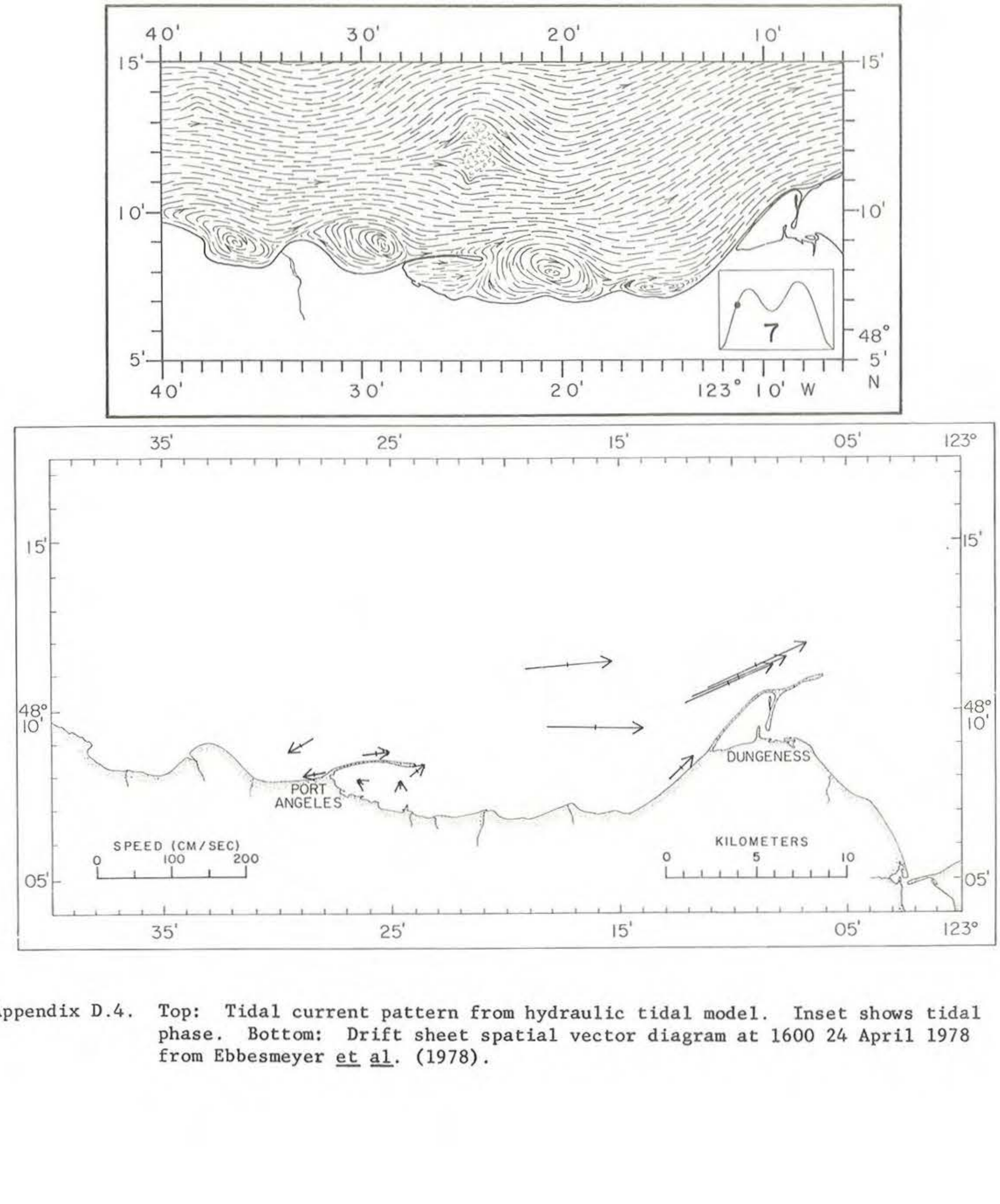
Appendix D.1. Top: Tidal current pattern from hydraulic tidal model. Inset shows tidal phase. Middle: Drogue trajectories on 1 September (left) and 20 August (right) 1970 from Tollefson et al. (1971). Bottom: Drift sheet spatial vector diagram at 1400 25 April 1978 from Ebbesmeyer et al. (1978). Speed scale applies only to spatial vector diagram.



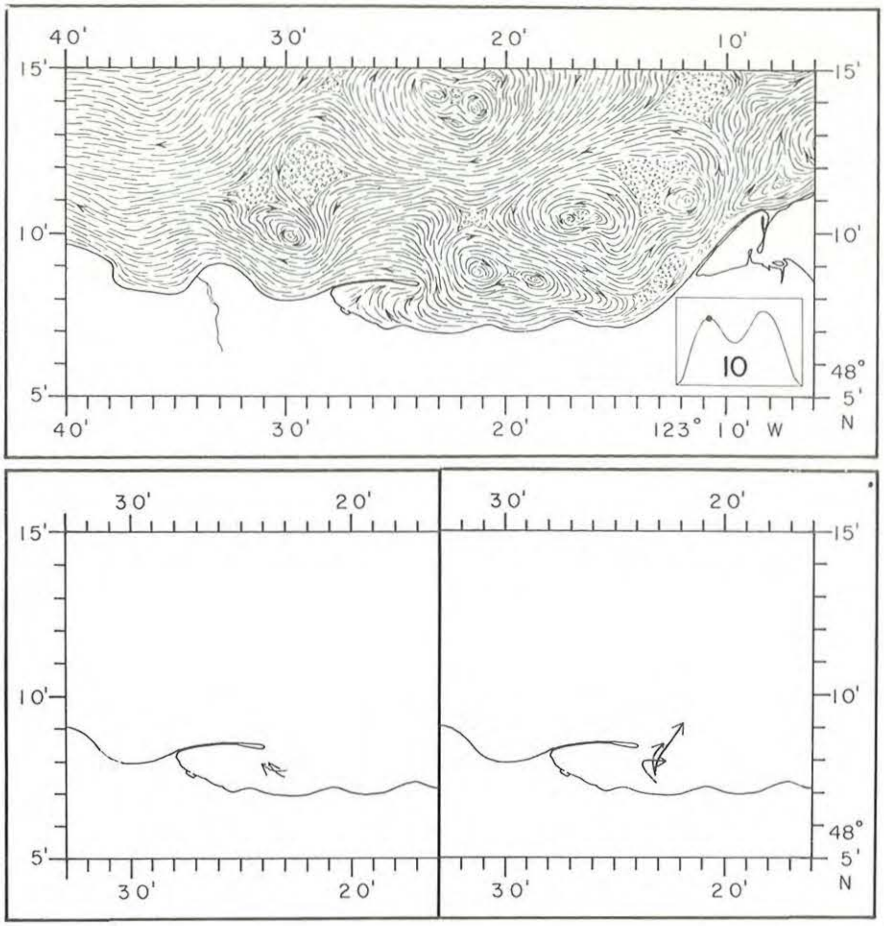
Appendix D.2. Top: Tidal current pattern from hydraulic tidal model. Inset shows tidal phase. Middle: Drogue trajectories on 28 July 1970 from Tollefson et al. (1971). Bottom: Drift sheet spatial vector diagram at 1300 24 April 1978 from Ebbesmeyer et al. (1978). Speed scale applies only to spatial vector diagram.



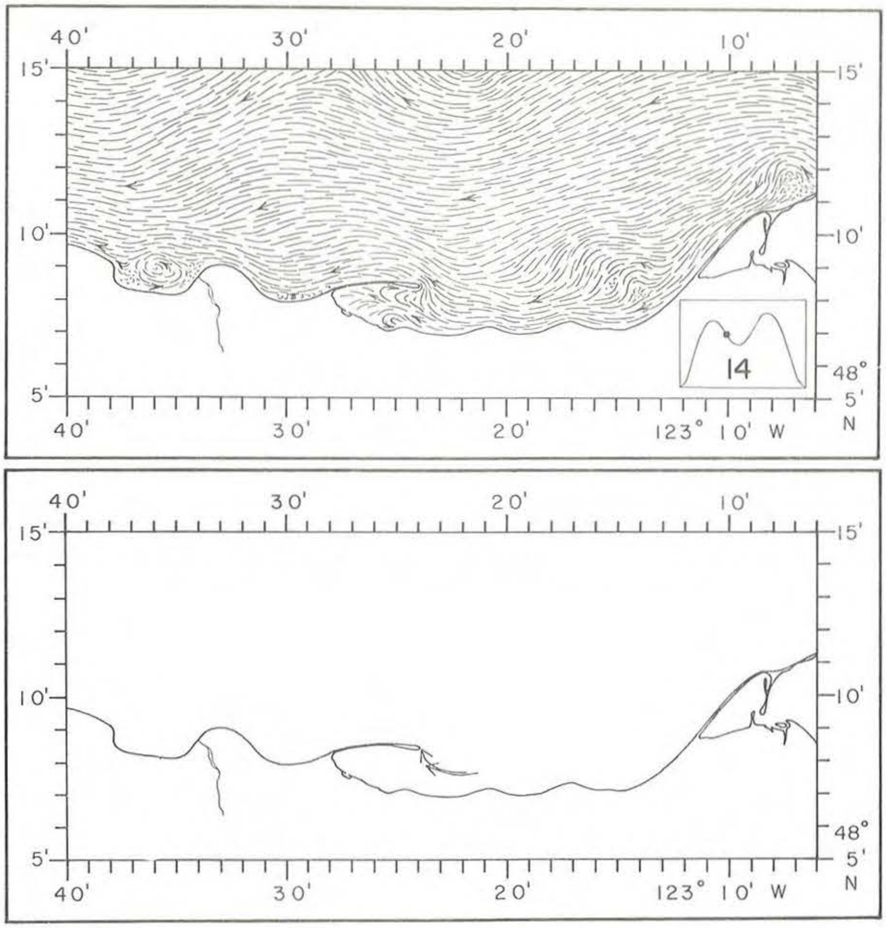
Appendix D.3. Top: Tidal current pattern from hydraulic tidal model. Inset shows tidal phase. Bottom: Drogue trajectories on 13 August (left) and 17 August (right) 1970 from Tollefson et al. (1971).



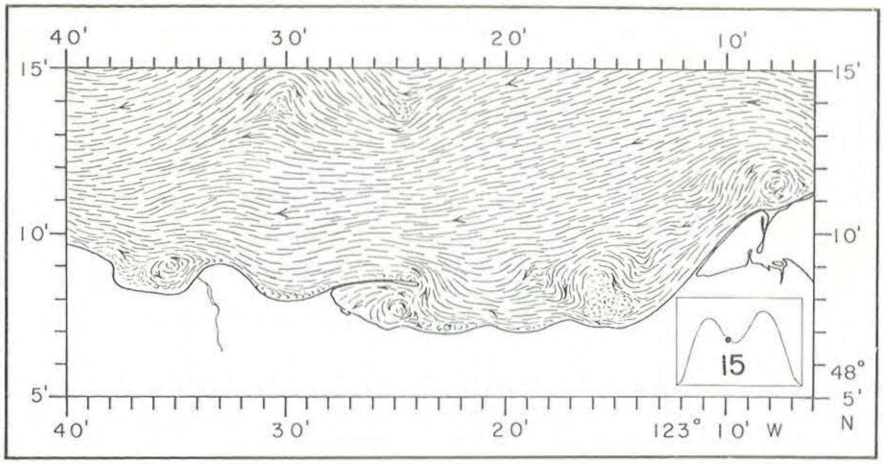
Appendix D.4. Top: Tidal current pattern from hydraulic tidal model. Inset shows tidal phase. Bottom: Drift sheet spatial vector diagram at 1600 24 April 1978 from Ebbesmeyer <u>et al</u>. (1978).

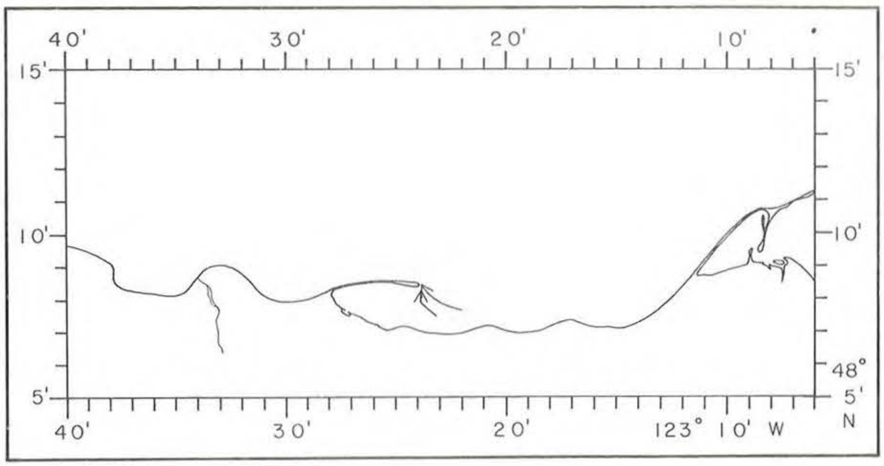


Appendix D.5. Top: Tidal current pattern from hydraulic tidal model. Inset shows tidal phase. Bottom: Drogue trajectories on 12 August (left) and 13 August (right) 1970 from Tollefson et al. (1971).

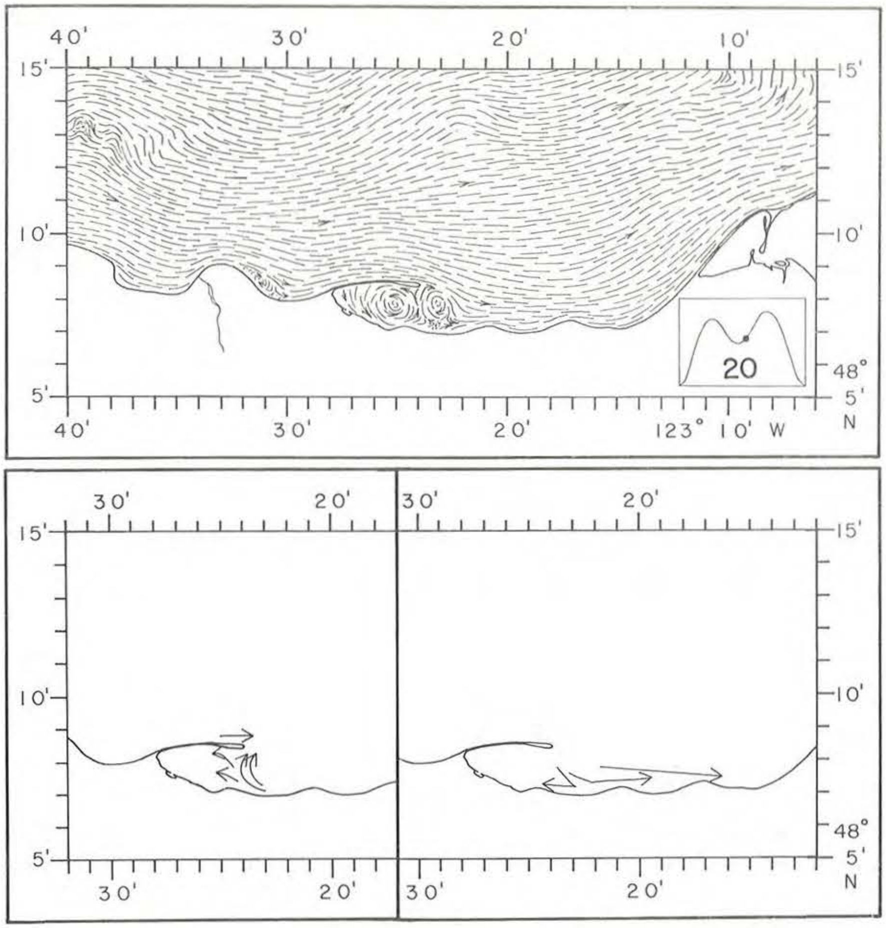


Appendix D.6. Top: Tidal current pattern from hydraulic tidal model. Inset shows tidal phase. Bottom: Drogue trajectories on 4 December 1970 from Tollefson et al. (1971).

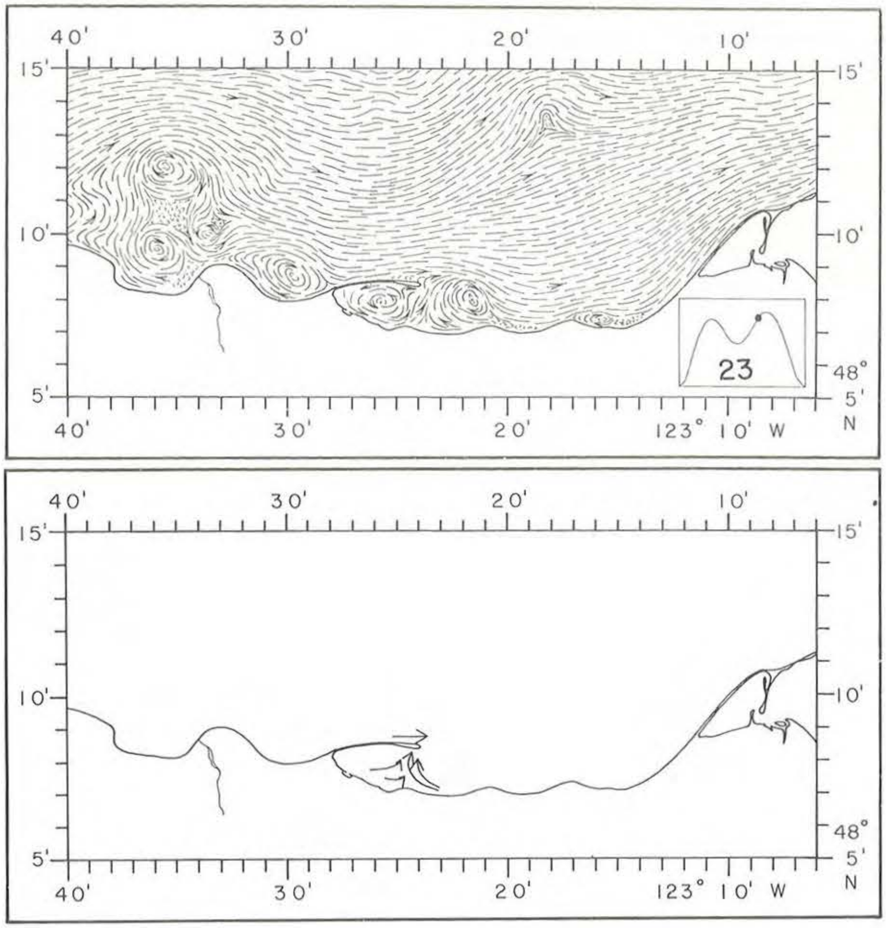




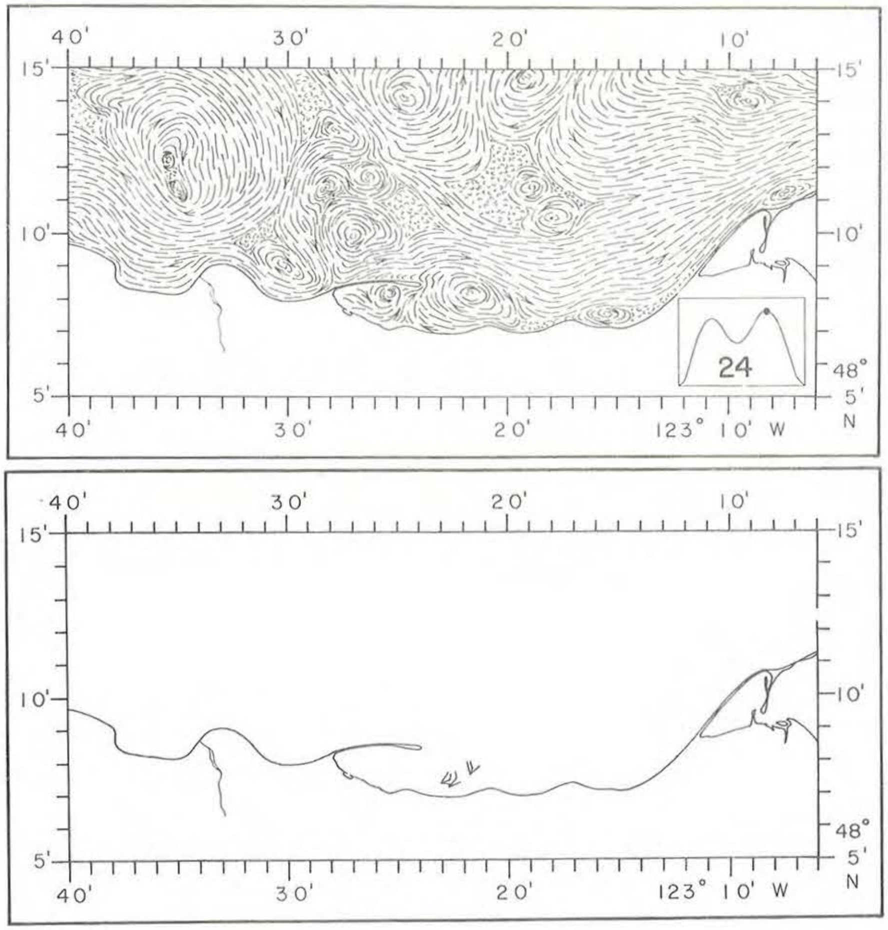
Appendix D.7. Top: Tidal current pattern from hydraulic tidal model. Inset shows tidal phase. Bottom: Drogue trajectories on 4 December 1970 from Tollefson et al. (1971)



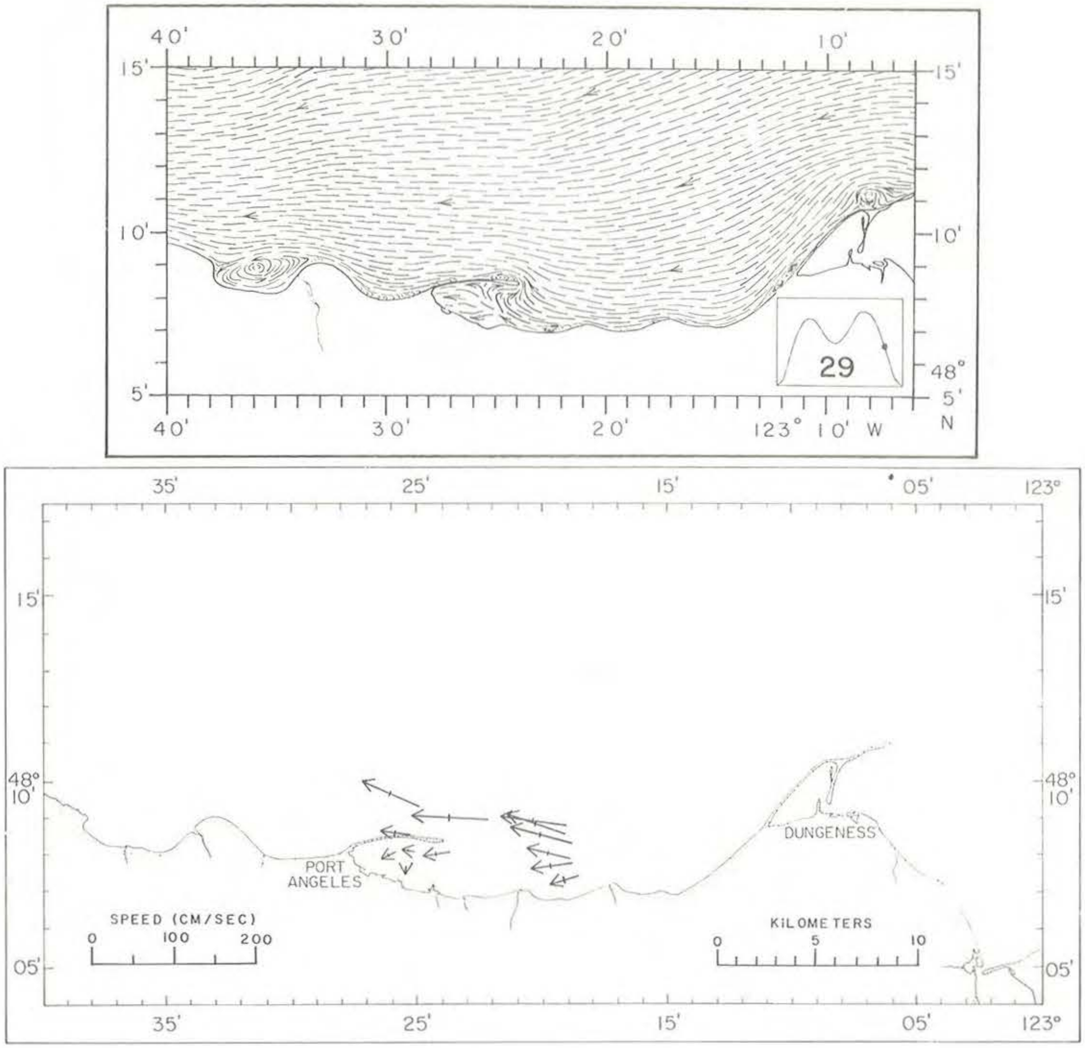
Appendix D.8. Top: Tidal current pattern from hydraulic tidal model. Inset shows tidal phase. Bottom: Generalized current pattern (left) from Charnell (1958); and drogue trajectories (right) on 28 August 1970 from Tollefson et al. (1971).



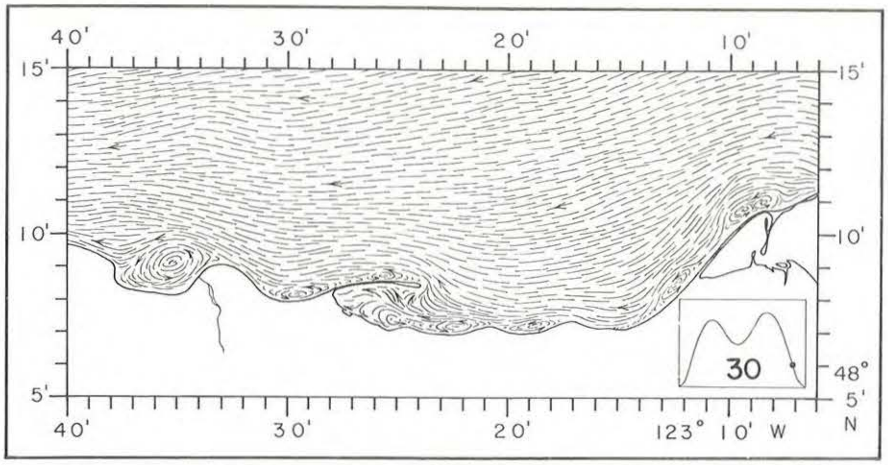
Appendix D.9. Top: Tidal current pattern from hydraulic tidal model. Inset shows tidal phase. Bottom: Generalized current patterns from Charnell (1958).

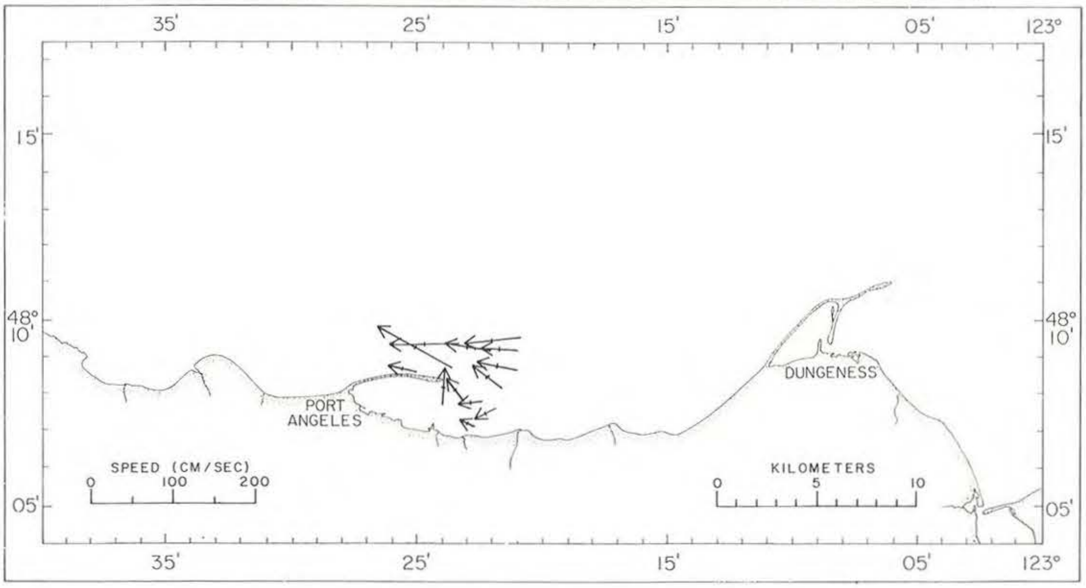


Appendix D.10. Top: Tidal current pattern from hydraulic tidal model. Inset shows tidal phase. Bottom: Drogue trajectories on 9 December 1970 from Tollefson et al. (1971).

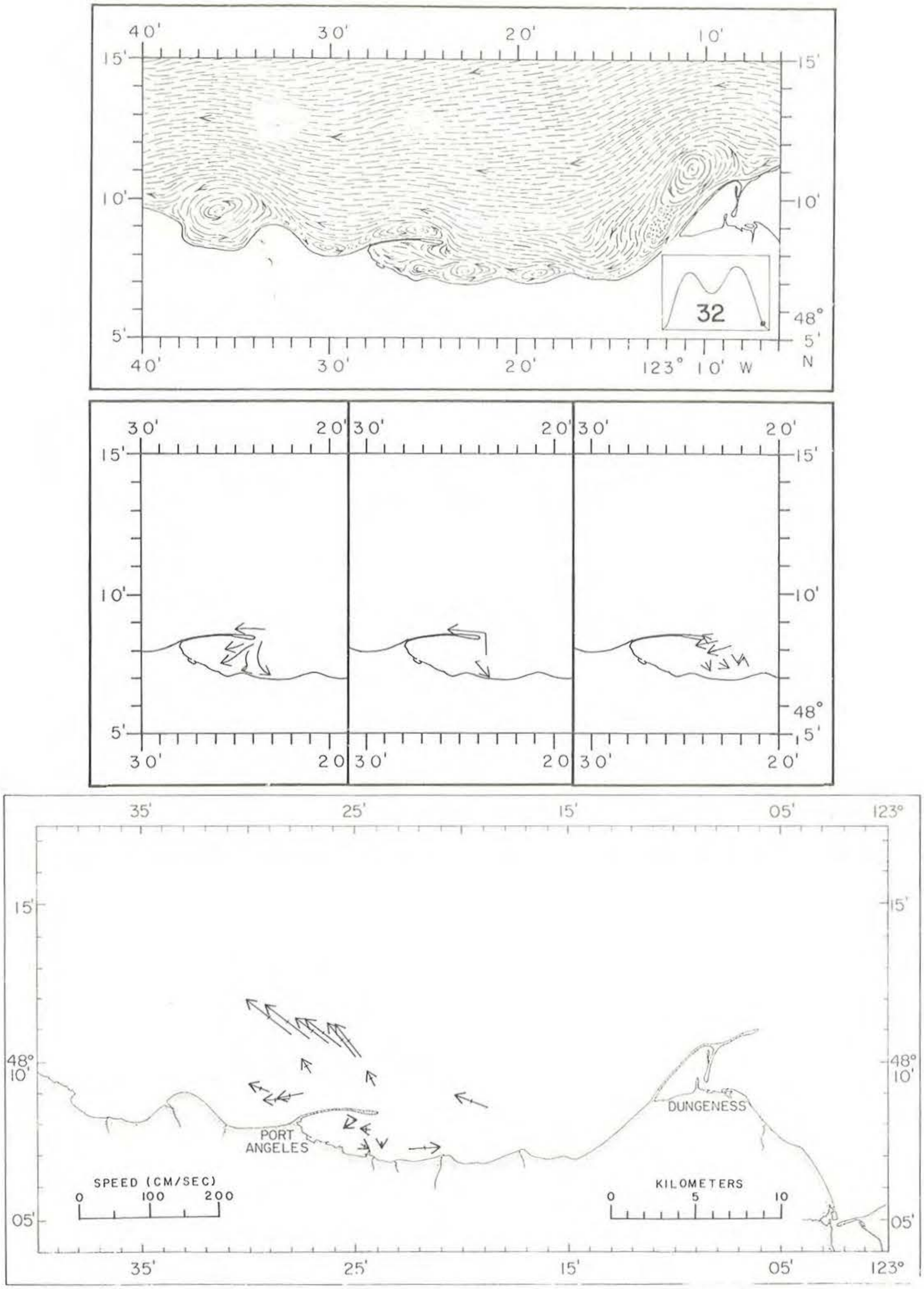


Appendix D.11. Top: Tidal current pattern from hydraulic tidal model. Inset shows tidal phase. Bottom: Drift sheet spatial vector diagram at 0900 24 April 1978 from Ebbesmeyer et al. (1978).





Appendix D.12. Top: Tidal current patterns from hydraulic tidal model. Inset shows tidal phase. Bottom: Drift sheet spatial vector diagram at 0800 25 April 1978 from Ebbesmeyer <u>et</u> <u>al</u>. (1978).



Appendix D.13. Top: Tidal current pattern from hydraulic tidal model. Inset shows tidal phase. Middle: Generalized current pattern (left) from Charnell (1958); and drogue trajectories on 22 July (middle) and 2 September (right) 1970 from Tollefson <u>et al</u>. (1971). Bottom: Drift sheet spatial vector diagram at 1100 25 April 1978 from Ebbesmeyer <u>et al</u>. (1978). Speed scale applies only to spatial vector diagram.